Reducing In-Home Exposure to Air Pollutants

Brett Singer (PI)
Woody Delp, Doug Black, Hugo Destaillats, Iain Walker
Lawrence Berkeley National Lab

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Disclaimer

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- Technical Advisory Committee: Wenhao Chen, Rob Hammon, Marla Mueller, Maziar Shirakh, and Bruce Wilcox

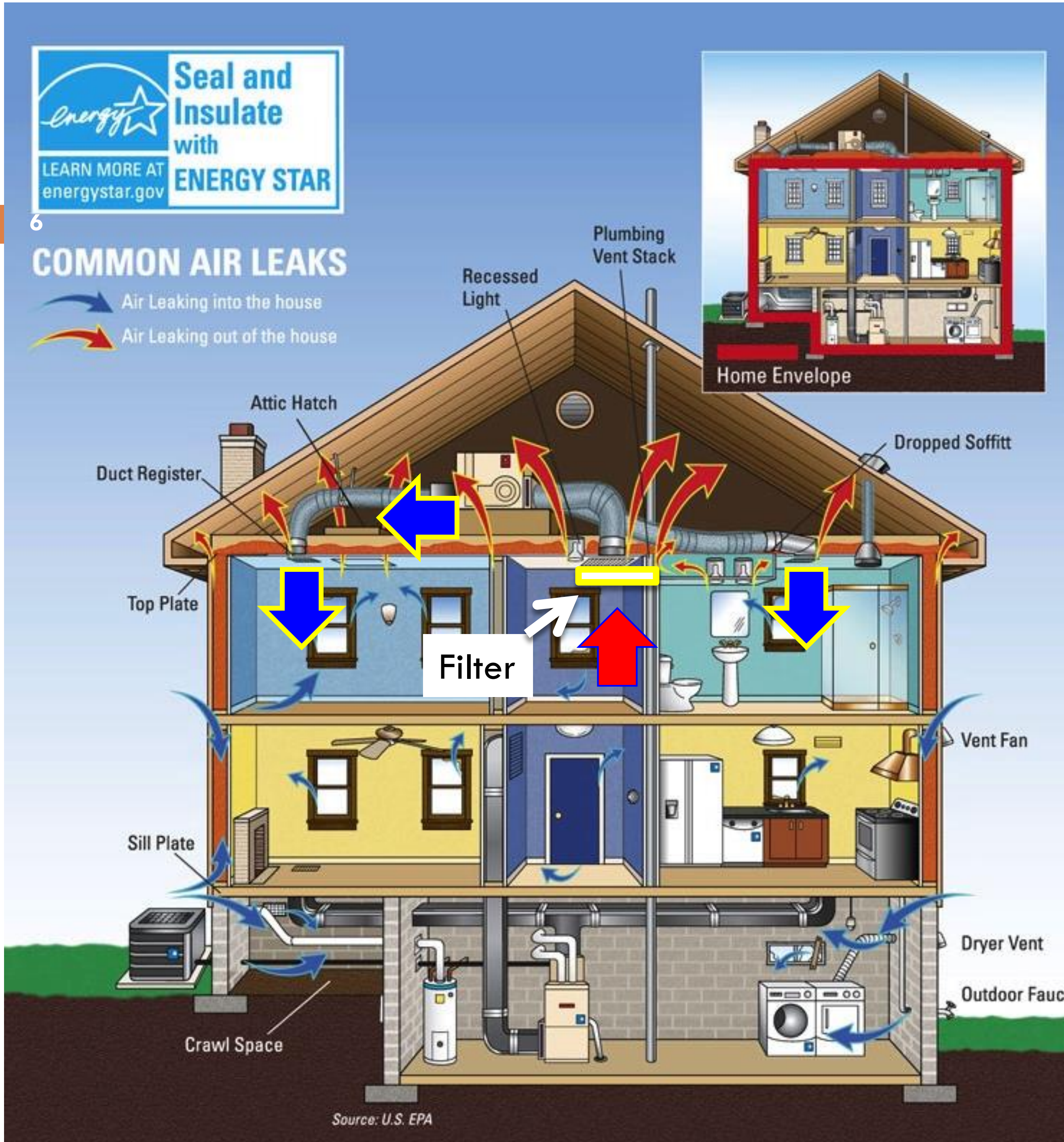
Homes can be designed to reduce our exposure to air pollutants

- We spend most of our time indoors, much of it at home
- Many California homes impacted by ambient air pollution
- Pollutant loss and removal as air enters and resides in buildings reduces concentrations relative to outdoors
- Engineered ventilation and filtration can further reduce exposures
- California requires new homes to be airtight for energy efficiency and to have mechanical ventilation
- ARB concerned that some types of mechanical ventilation could increase in-home exposure to outdoor pollutants

Study Objectives

- Quantify effectiveness of ventilation and filtration systems at reducing in-home exposures to pollutants
- Focus on $PM_{2.5}$, ultrafine particles and black carbon (diesel PM) from outdoor sources
  - Secondary focus on ozone, VOCs and indoor generated particles
- Identify compatible low-energy systems suitable to California and quantify energy use of these systems relative to Reference

Residential Airflows



Windows closed: air enters via cracks & gaps

Recirculation through heating & cooling forced air unit (FAU) –

Envelope air-sealed for energy efficiency

Airtight homes have base mechanical ventilation
- Exhaust
- Supply
- Balanced

Enhanced air cleaning options

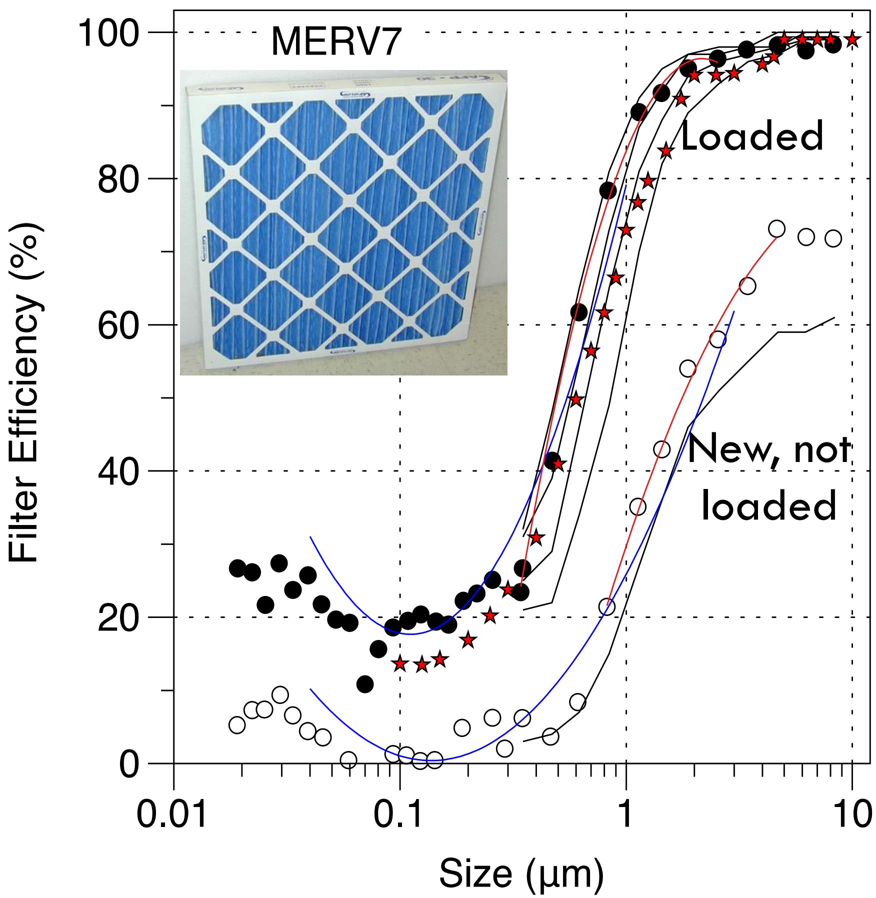
- Indoor-generated pollutants
  - Filter on forced air unit (FAU); helps when heating or cooling
  - Operate FAU specifically to clear air
  - Room air cleaners*

- Outdoor pollutants
  - Filter pollutants from indoor air after entry
  - Supply or balanced ventilation: Add filter in-line
  - Exhaust ventilation: Envelope acts as a filter

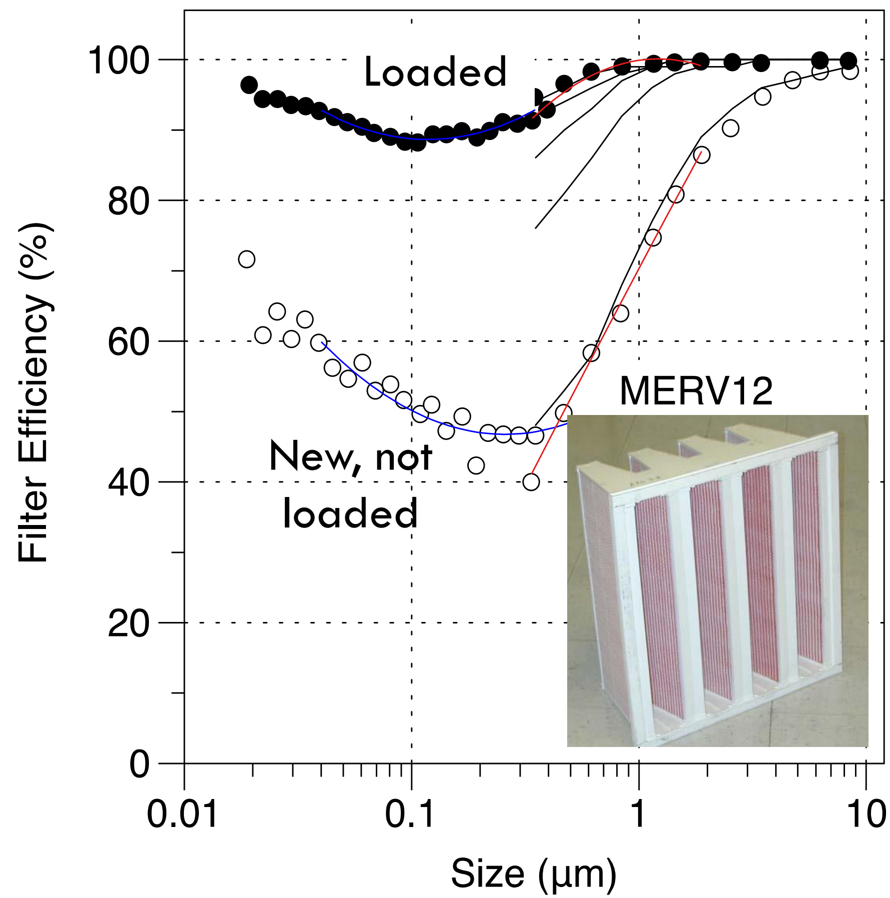
*Not a focus of this study; examined in other ARB sponsored studies

Filter effectiveness indicated by MERV rating

MERV7



MERV12



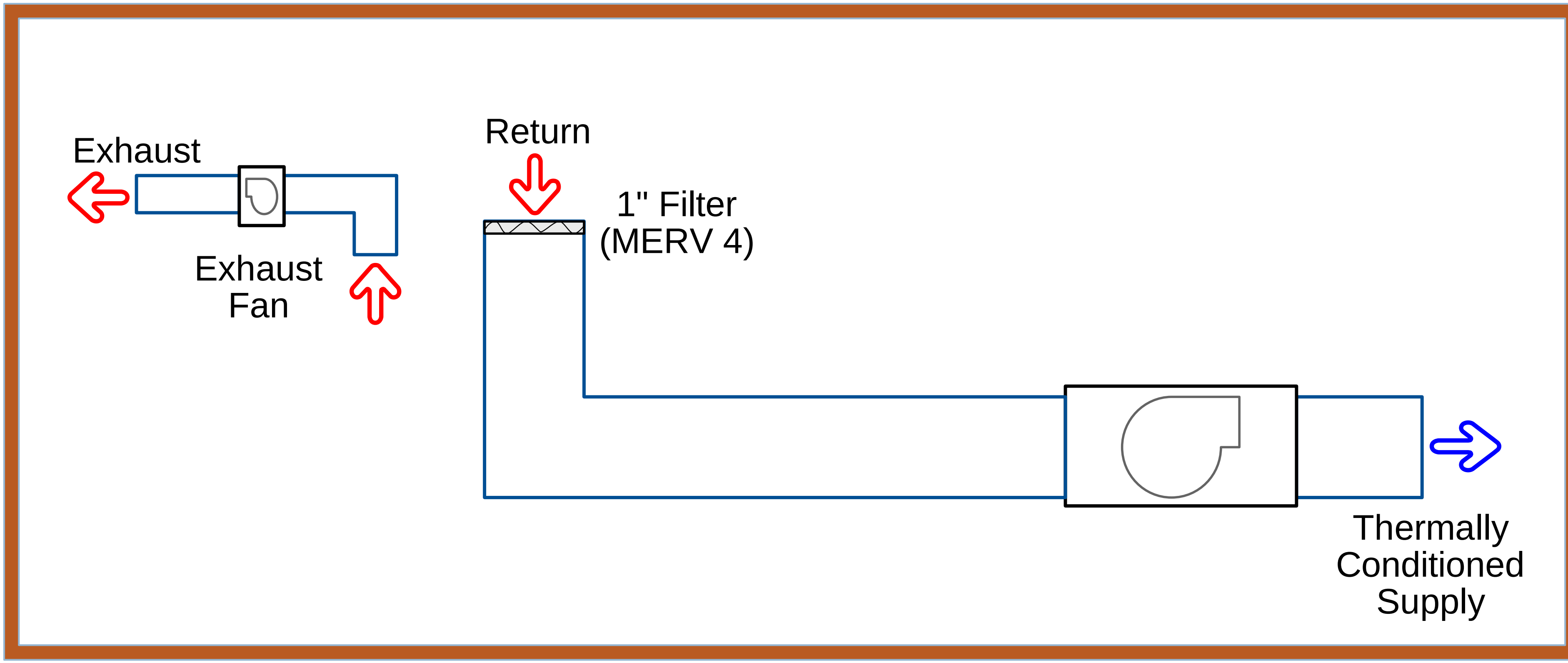
Ventilation & Enhanced Pollutant Removal

- Reference + 7 systems with enhanced removal
- Exhaust, supply and balanced ventilation
- Particle filtration:
  - MERV8 to MERV13 on supply
  - MERV4 to MERV16 or electrostatic precipitator on FAU
  - HEPA on FAU bypass, portables with HEPA
- VOC removal technologies
  - Activated carbon
  - Chemisorbent
  - Room temperature catalyst

Approach

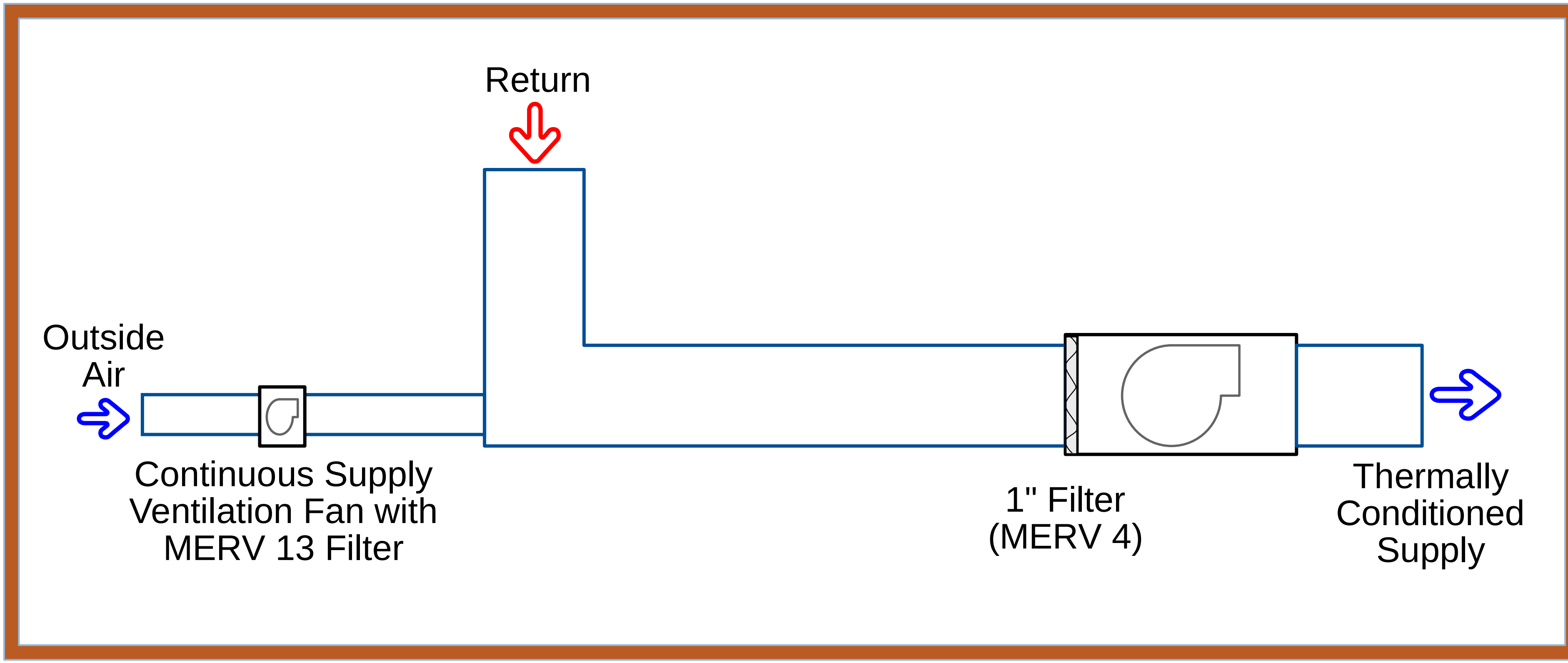
- Compare systems with enhanced pollutant removal to each other and to a common, “reference” system
- Install in test house and operate 5-7 d in summer & fall/winter
- Measure air pollutants and energy
- Evaluate particle removal for indoor source (cooking)
- Key metrics are ratio of indoor-to-outdoor (I/O) concentrations, percent reductions in pollutant levels, and annual energy

Reference:
Exhaust ventilation; MERV4 on FAU t-stat control



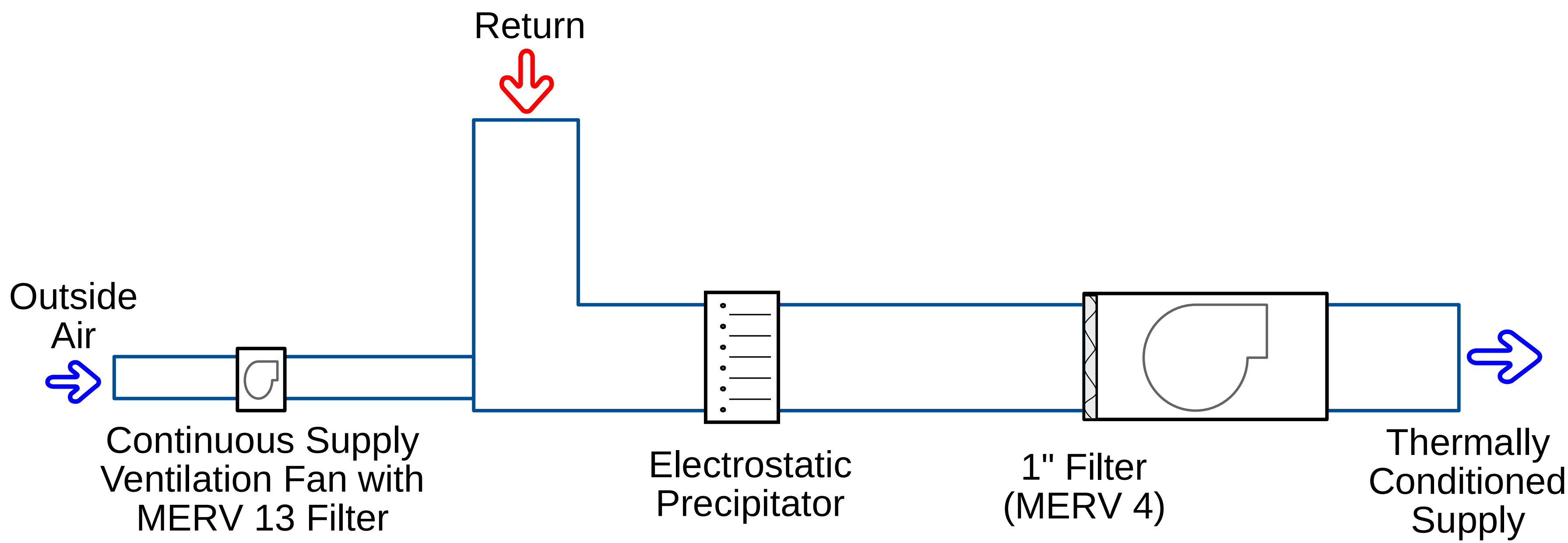
Bath fan draws 6.5W

A: MERV13 on continuous supply; MERV4 on FAU t-stat control



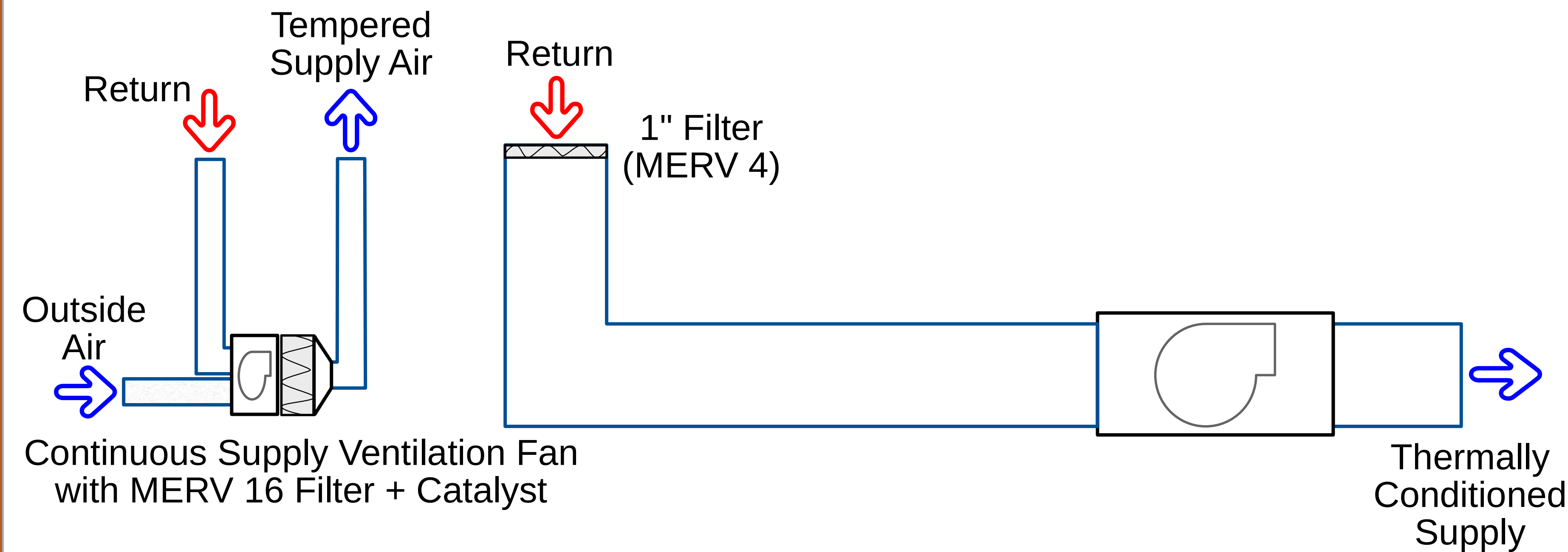
Extra power relative to Reference : 2W (est.)

B: MERV13 on continuous supply; electronic air cleaner (ESP) +MERV4 on FAU w/t-stat control



Extra power relative to Reference: 20 W

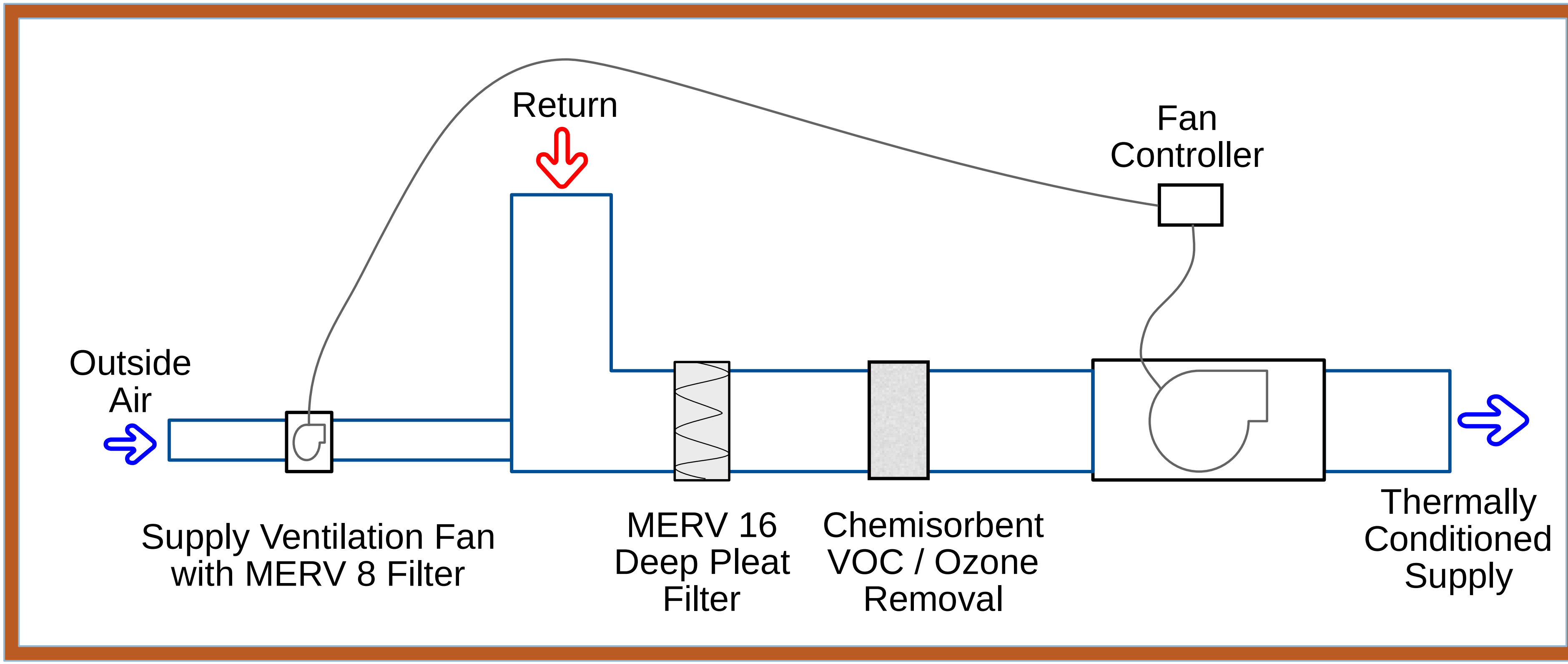
C: MERV16 w/catalyst[1] on blended supply; MERV4 on FAU t-stat control



[1]For VOC removal

Extra power relative to Reference: 38 W

D: MERV8 on supply, MERV16 + chemisorbent[1] on FAU operating 20 min each hour

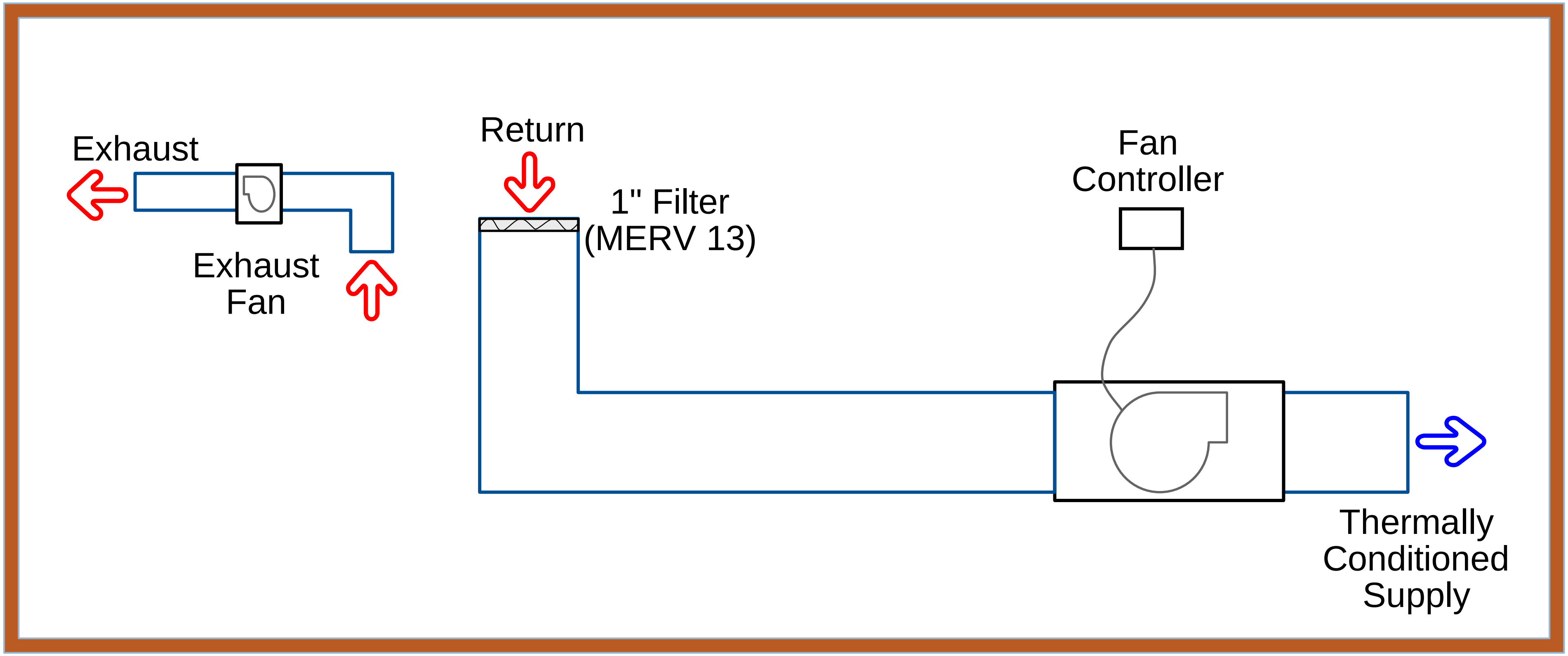


[1]For VOC removal

Extra power relative to Reference: 240 W*

*Could be reduced with efficient FAU motor

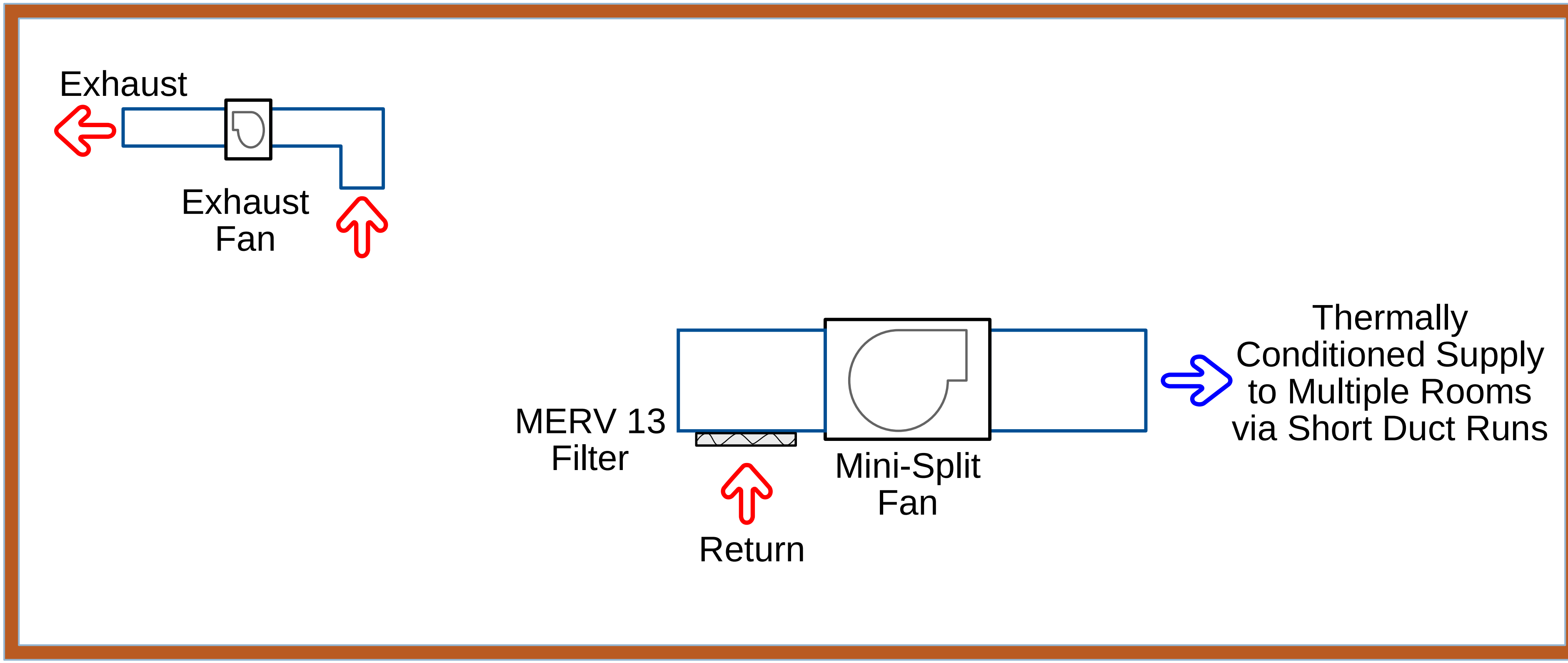
E: Exhaust ventilation + MERV13 on FAU operating min. 20 min each hour



Extra power relative to Reference: 235 W*

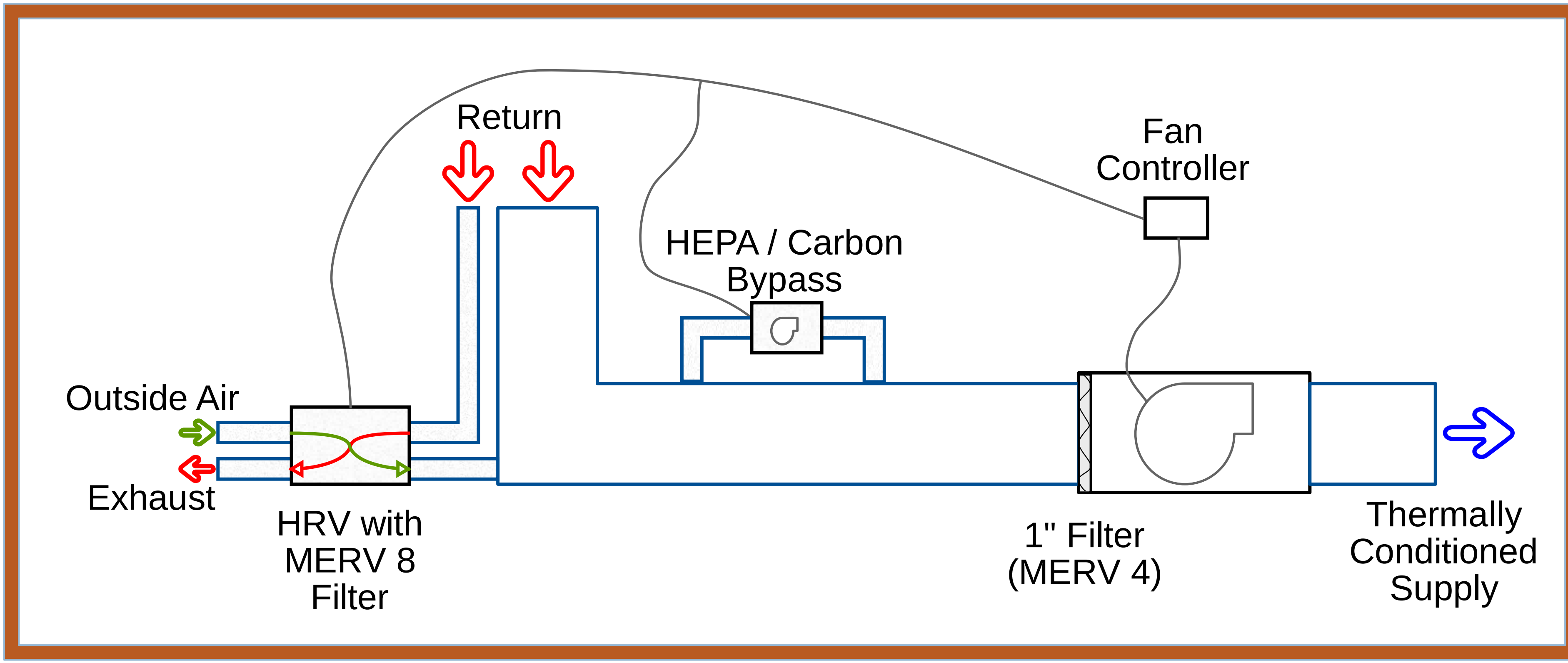
*Could be reduced with efficient FAU motor

F: Exhaust ventilation + MERV13 on “Mini-split”



Extra power relative to Reference: 100 W

G: MERV8 on supply; HEPA+ activated carbon[1] on FAU operating 20 min each hour

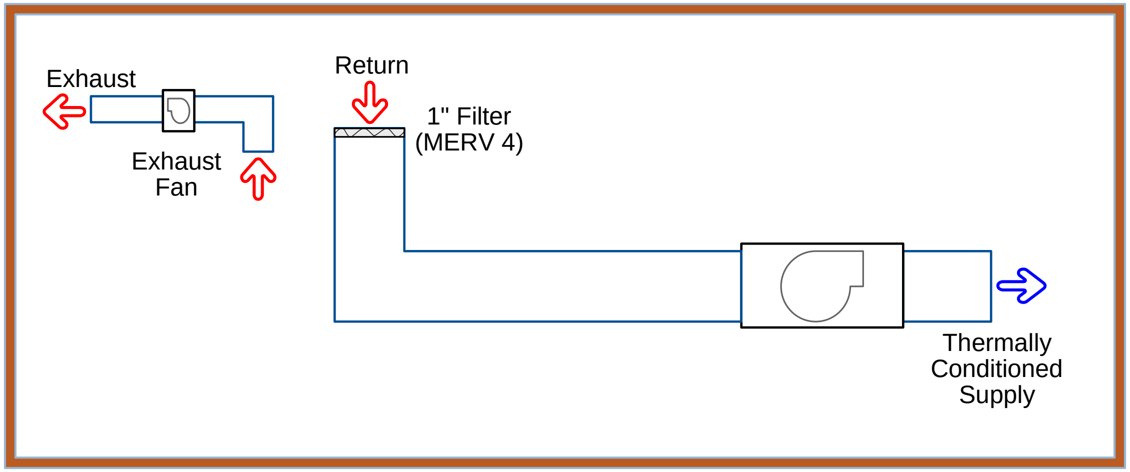


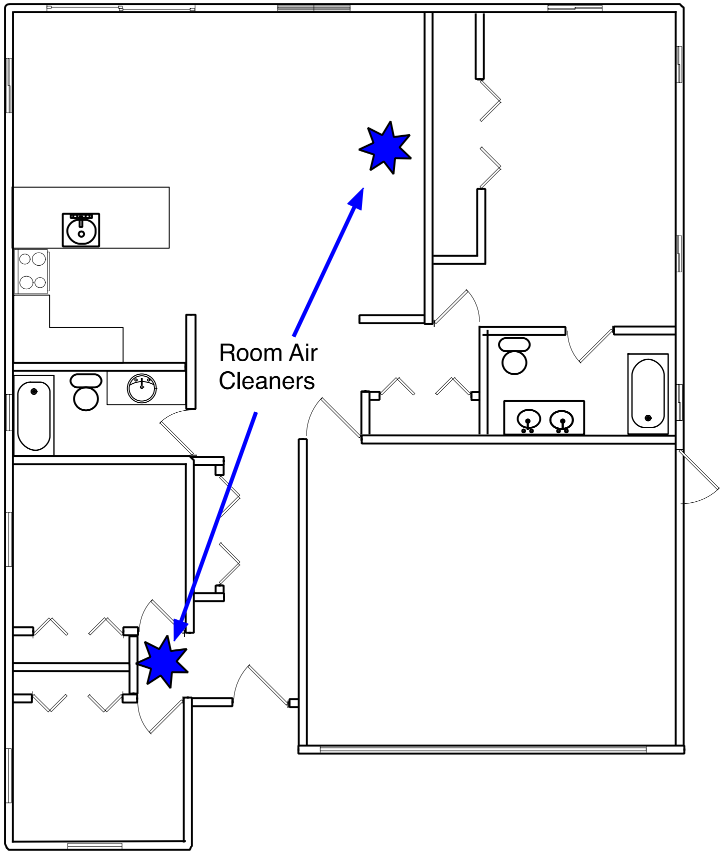
Extra power relative to Reference: ~300 W*

*Includes estimated energy recovery by HRV. Could be reduced with efficient blower motor.

[1]For VOC removal

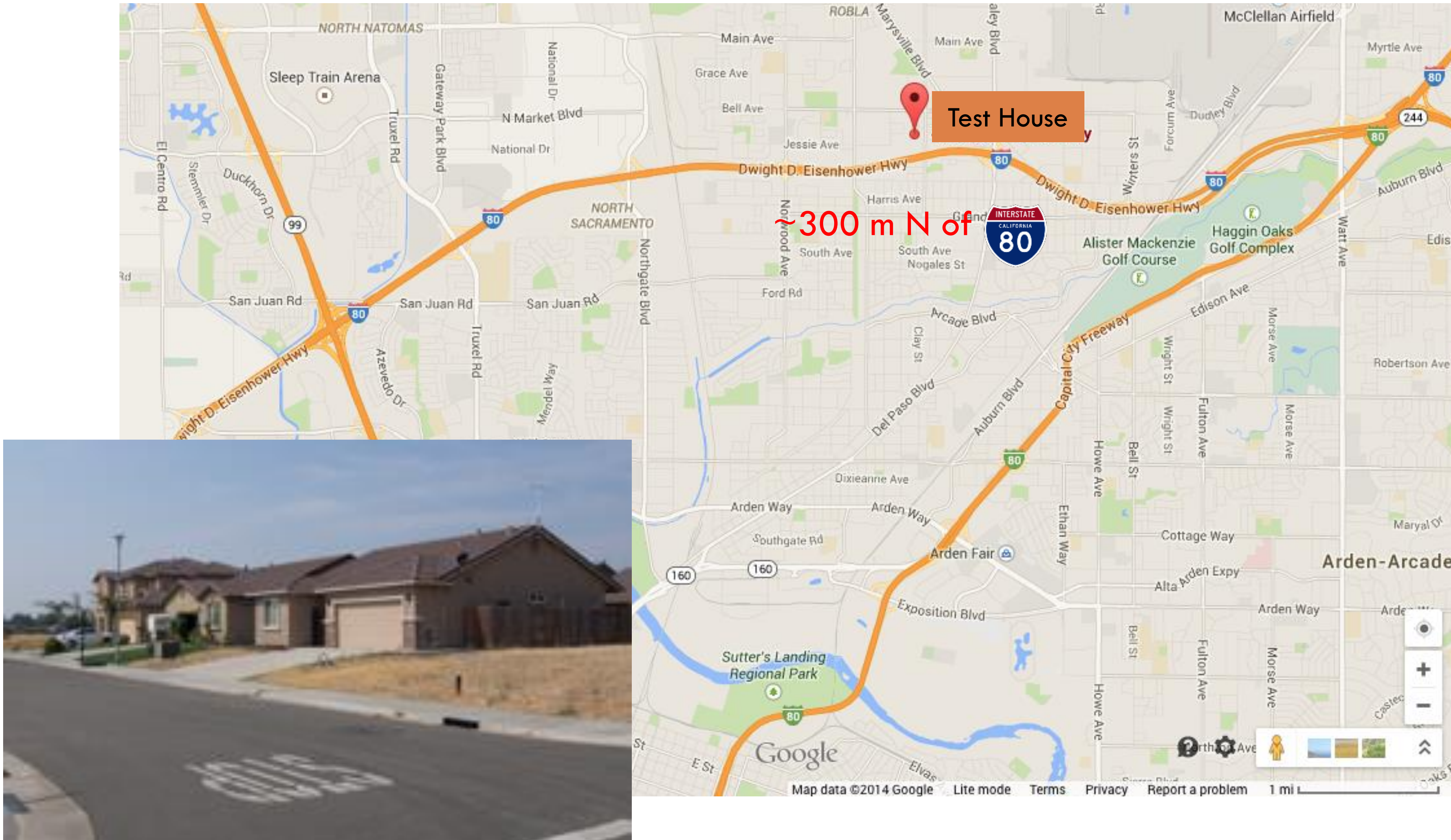
Reference + Portable Air Filtration Units:





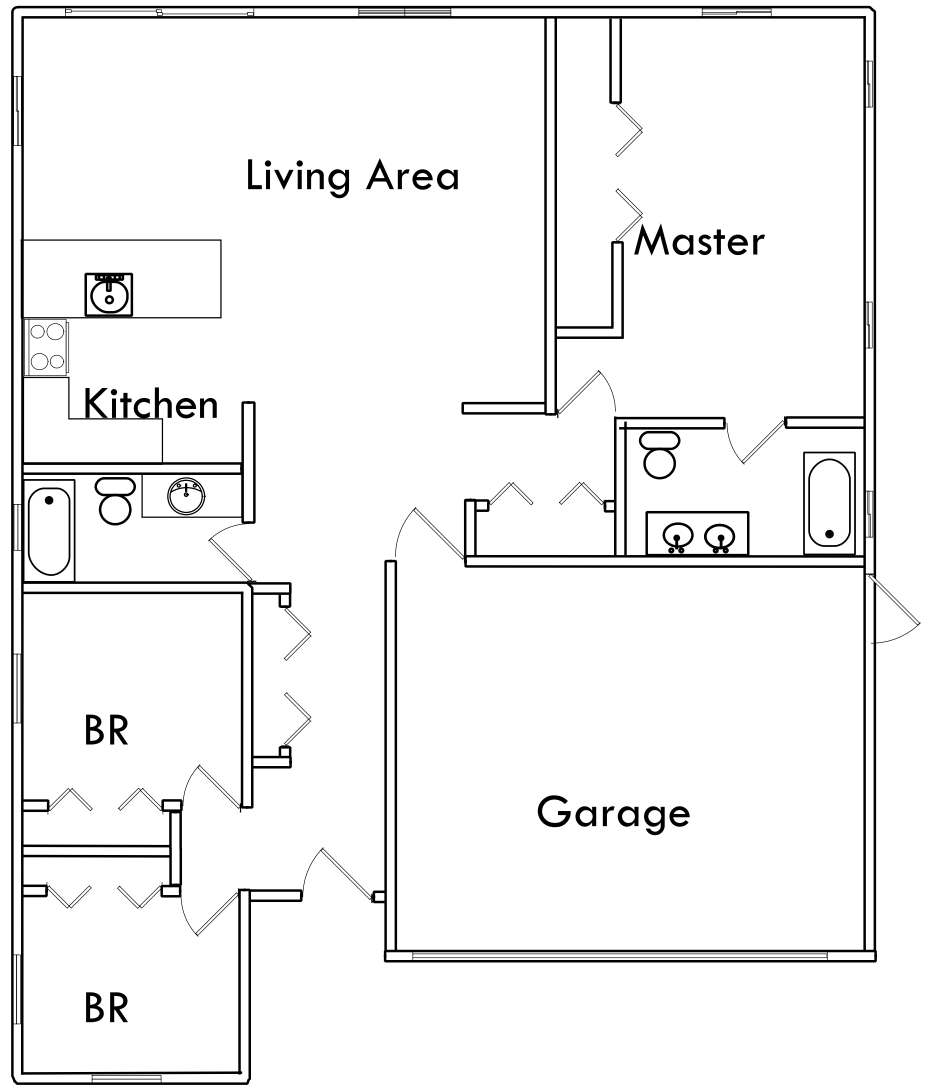
Extra power relative to Reference: 8-30 W

Test House: Impacted by I-80, Sacramento



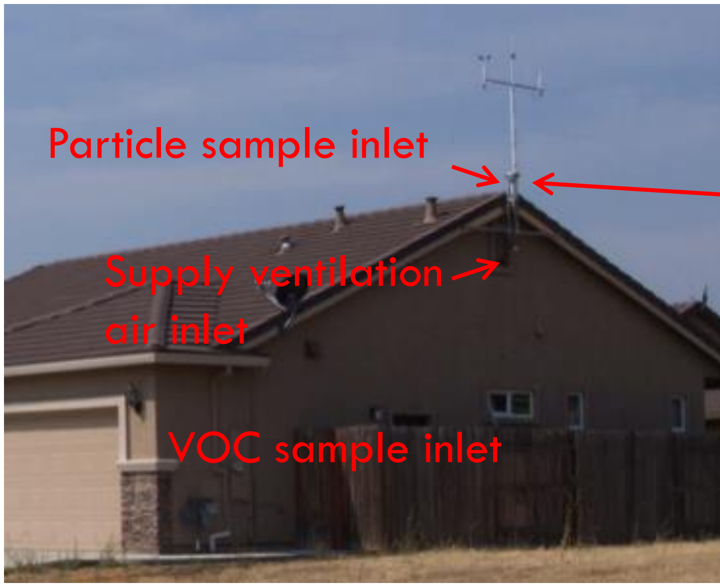
Test House – Typical California Construction

- Built 2006
- 1,200 ft^2
- 3 bedroom, 2 bath
- One story slab foundation
- FAU in attic

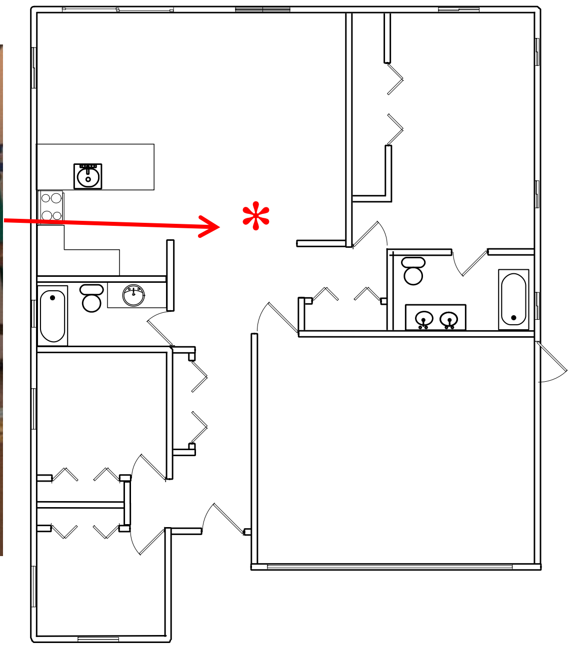


Sampling locations

Outdoor



Indoor



At roofline just above the main inlet

Centrally located

Indoor & outdoor sample lines had equal length and turns!

Continuous pollutant measurements

CPCs

3787

Total count

6 nm - 2.5µm

3781 w/ Size Selector

Total count

100nm - 2.5µm

Met One

OPC

0.3µm - 0.4µm
0.4µm - 0.5µm
0.5µm - 0.7µm
0.7µm - 1.0µm
1.0µm - 2.5µm

Aethalometer

BC & UV

2B Technologies

Ozone

DustTrak

$PM_{2.5}$

Mass estimated from size-resolved particle number concentrations

Speciated VOC and Volatile Aldehydes

- 31 VOCs, indoor and outdoor origin
- 24-h integrated samples for 2-4 d in summer
- 3 systems w/VOC removal technology and Reference

Robustness and data integrity

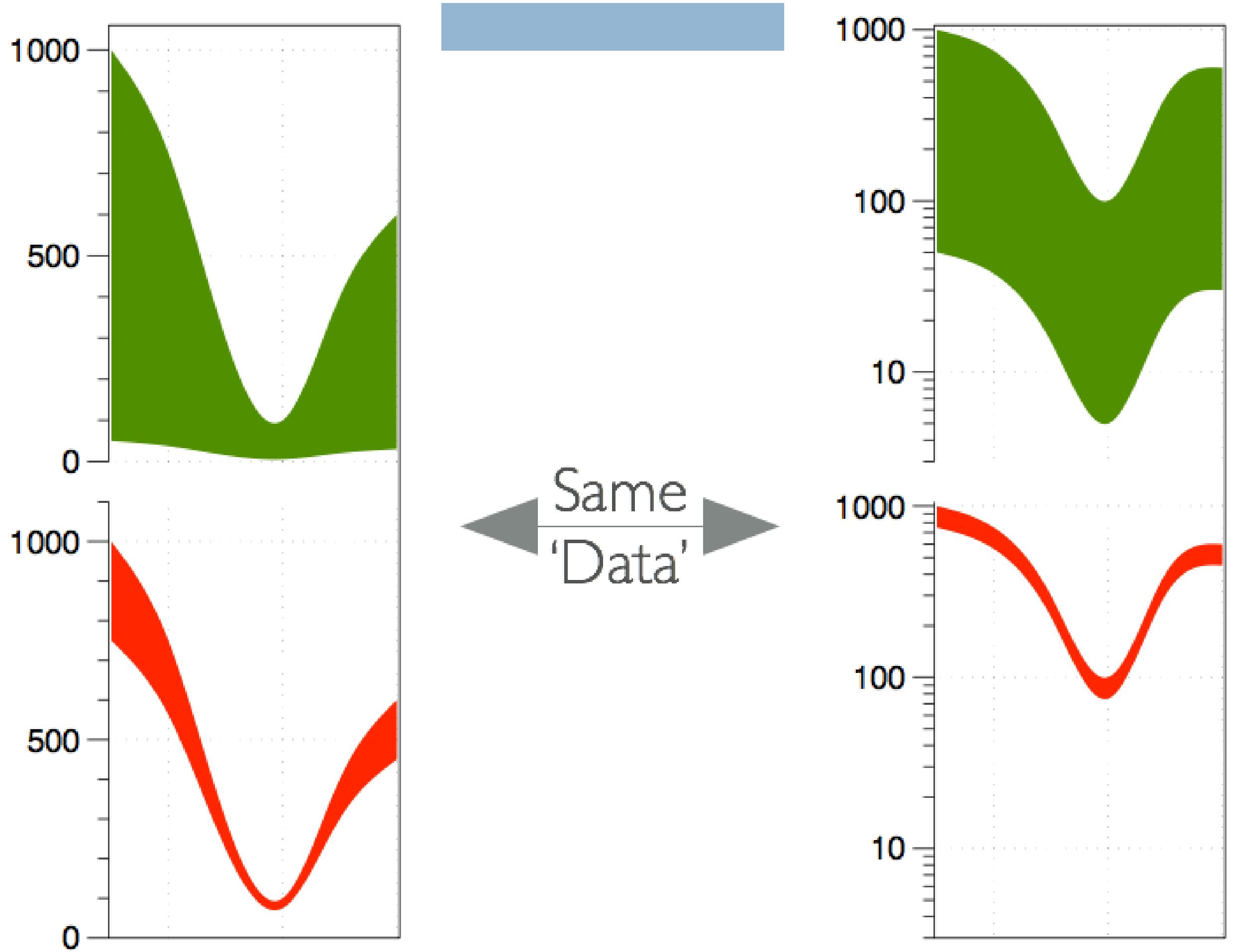
- Parallel systems switching indoor and outdoor

- Continuous cross-checks of particle instruments
- Continuity through any single instrument failure

Key parameter is indoor/outdoor ratio.
Log scale shows consistent results as levels vary.

I/0 0.05
95% Reduction

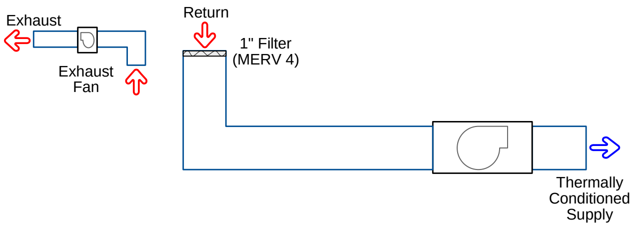
I/0 0.75
25% Reduction

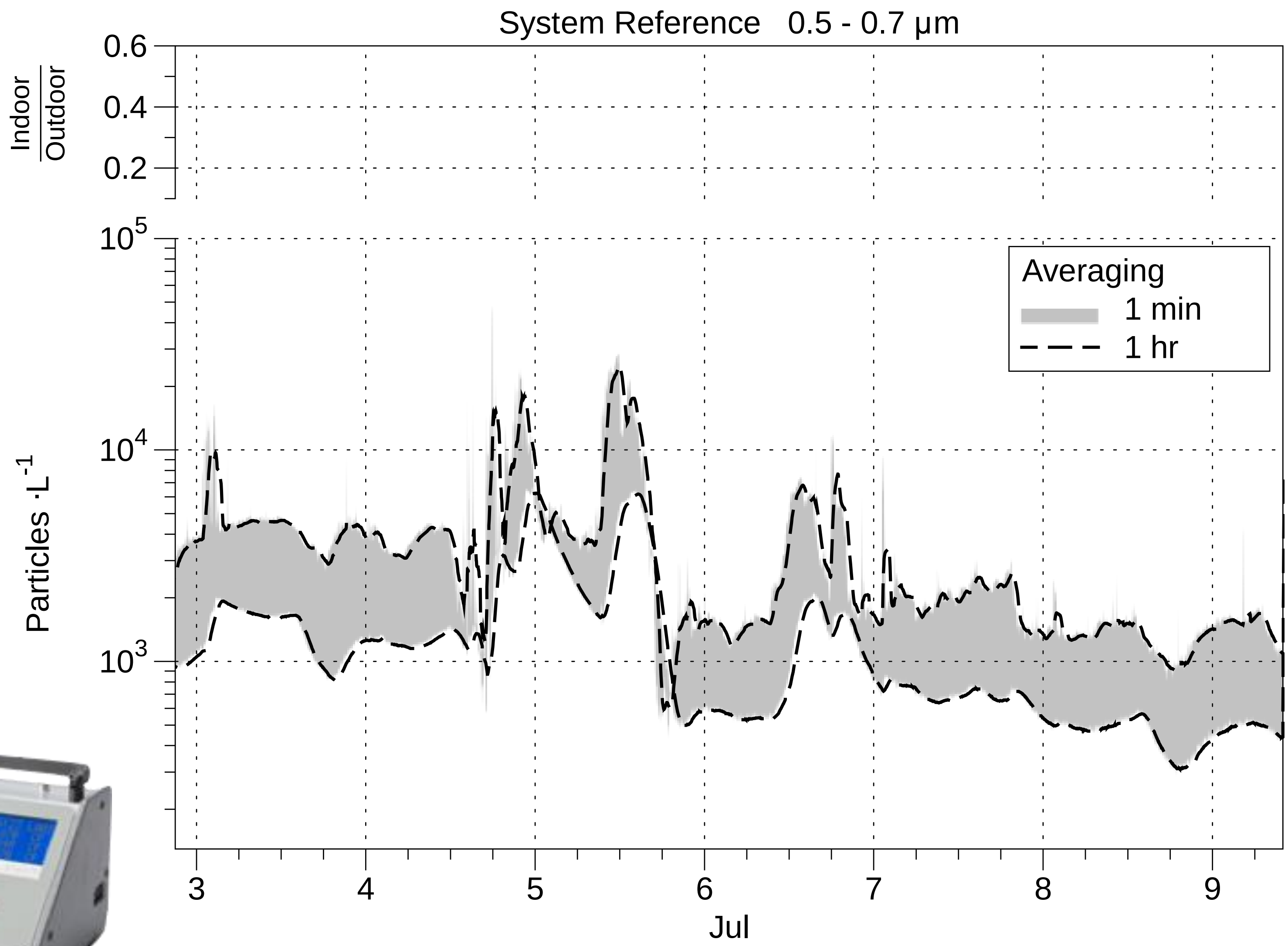


Illustrates the absolute reduction

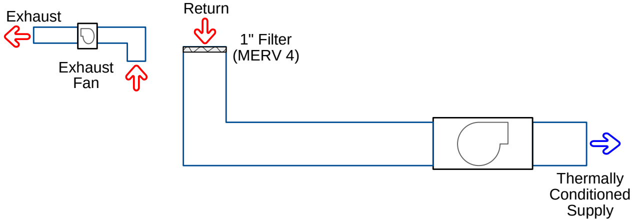
Illustrates the relative reduction

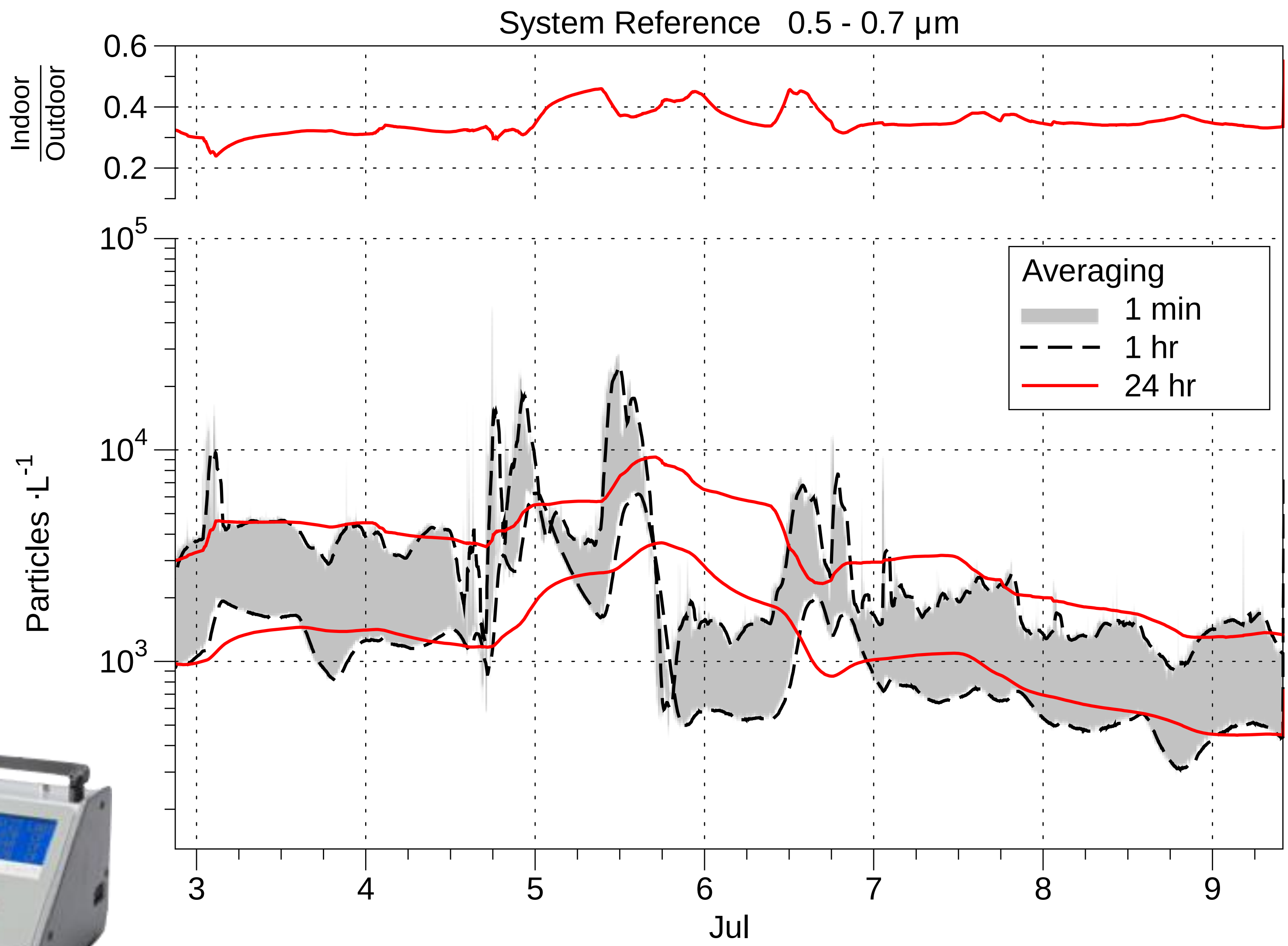
Example Results: Reference



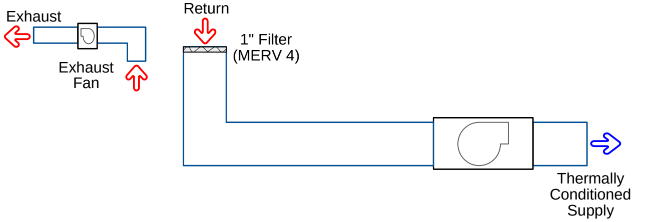


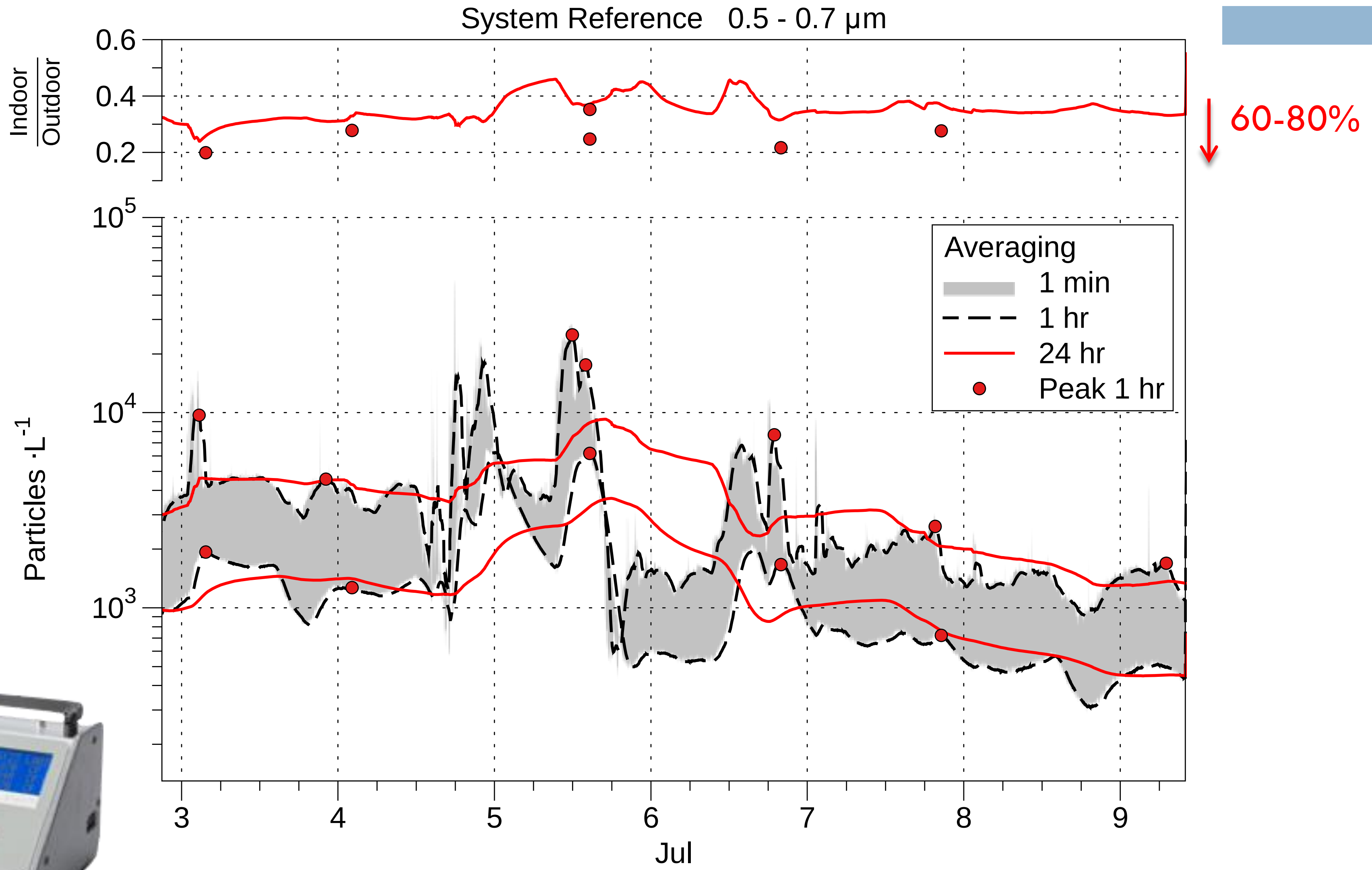
Example Results: Reference



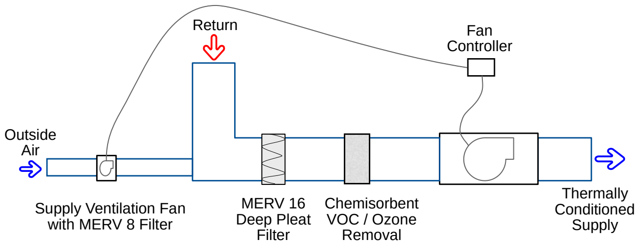


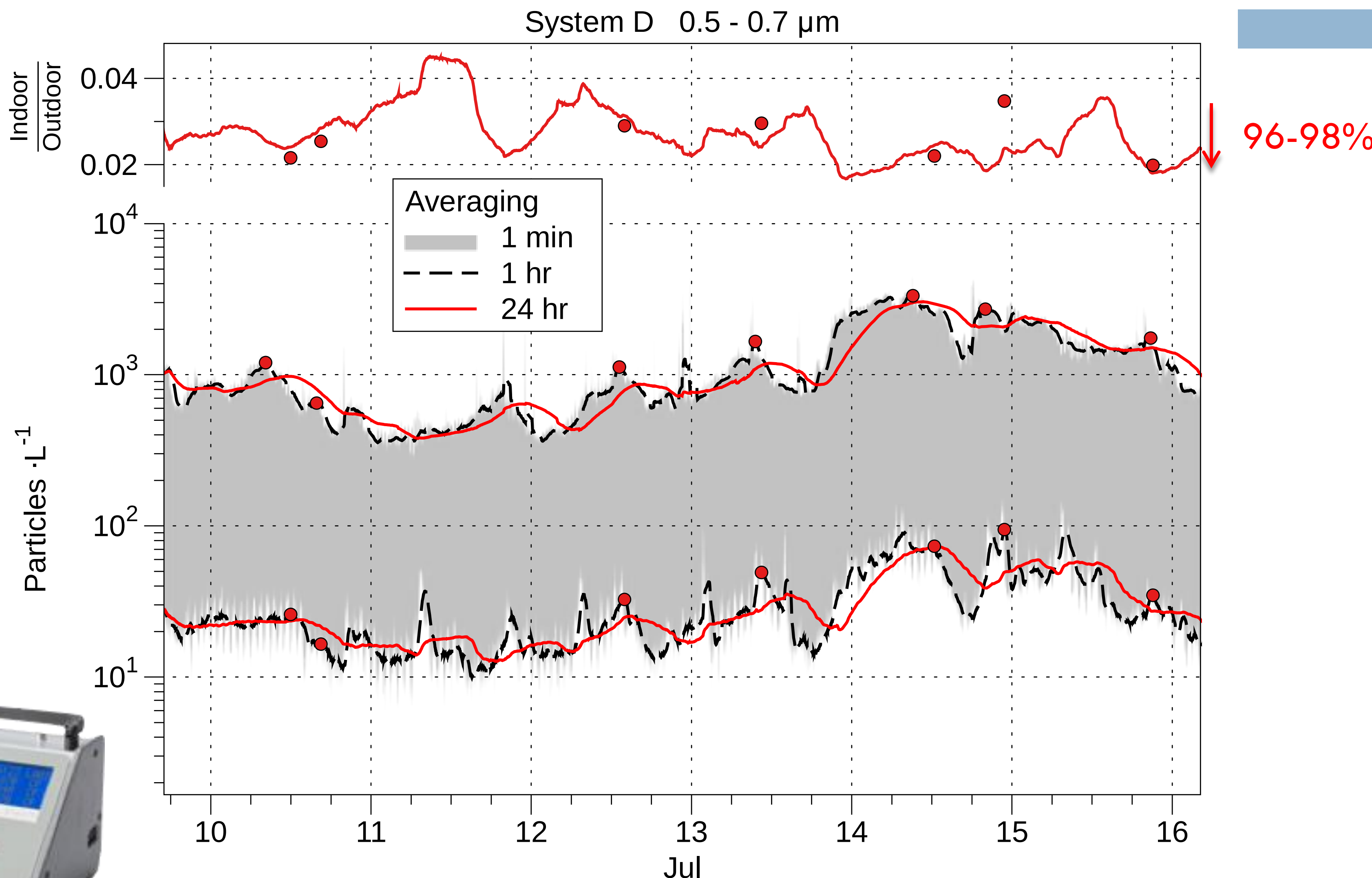
Example Results: Reference





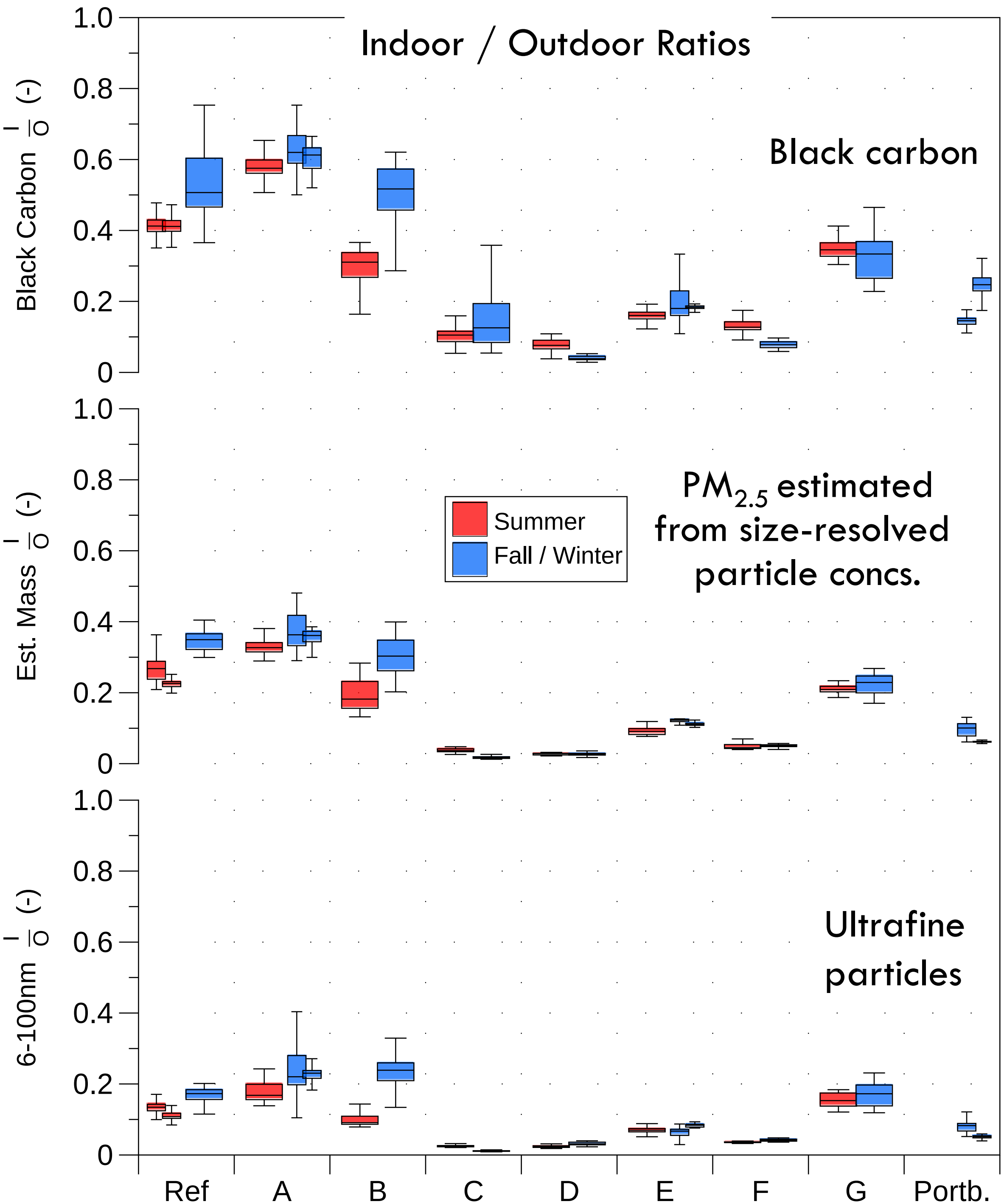
Better Performance: System D (MERV16)





Summary Results: Outdoor Particles

- Effectiveness varied: UFP > $PM_{2.5}$ > BC
- Best particle removal:
  - MERV16 on supply (C)
  - MERV16 on FAU (D)
  - MERV13 on minisplit (F)
  - Portables with HEPA
  - MERV13 on FAU (E)
- Similar results in summer & fall/winter, except for Sys B with ESP on t-stat

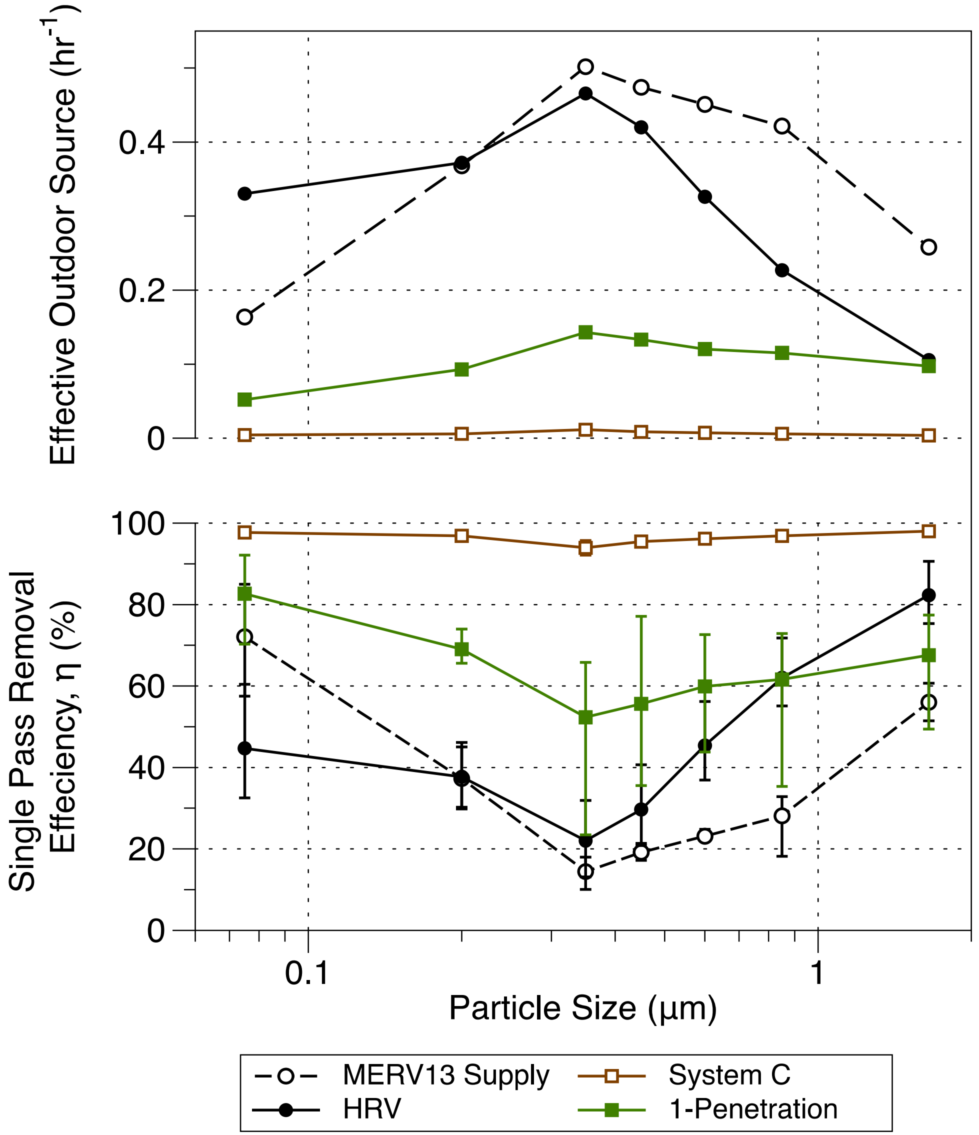


Percent reductions in particle concentrations compared to outdoors (SU, F/W)

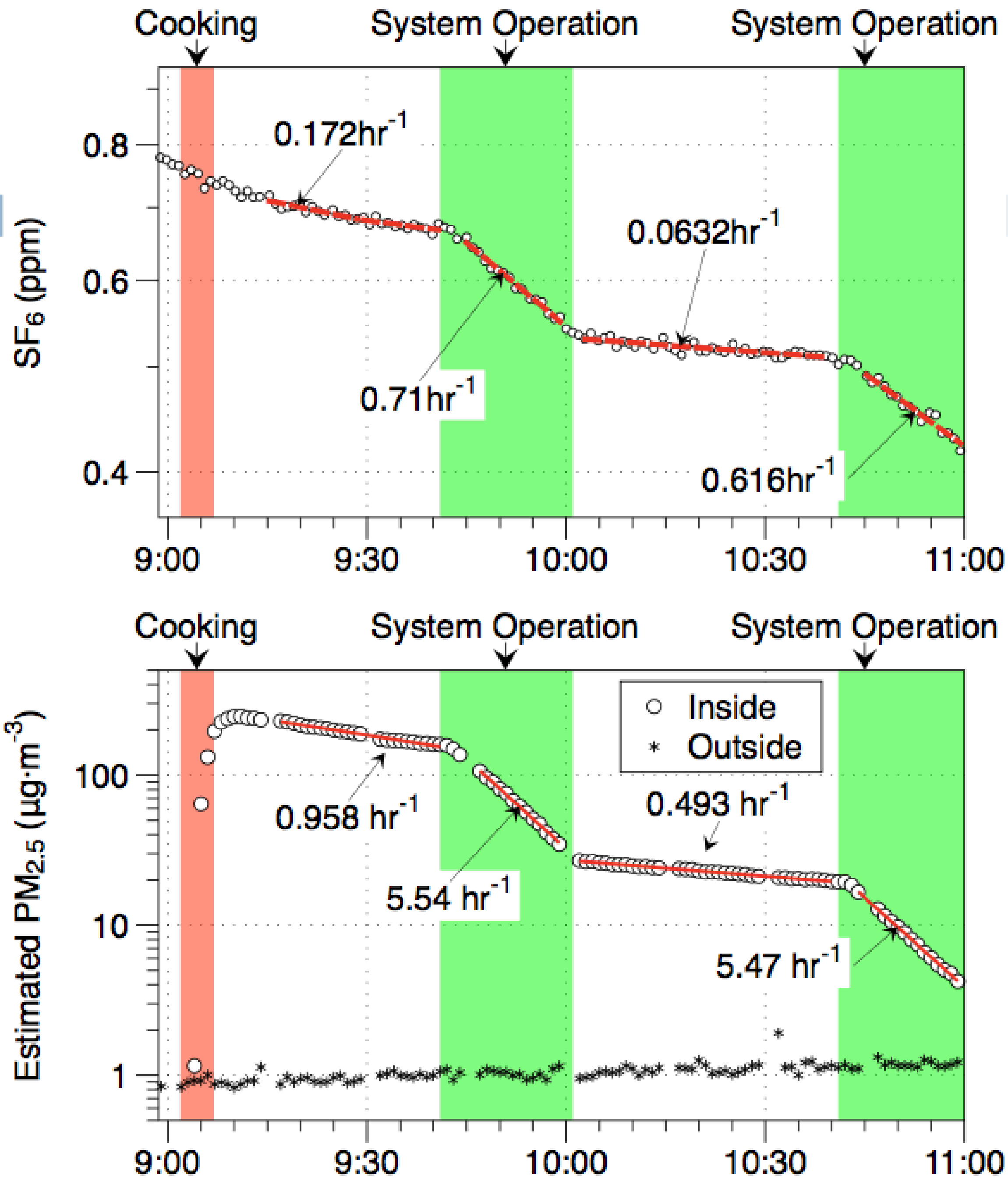
System	$PM_{2.5}$	Black carbon	Ultrafine particles
Ref: modestly tight shell + exhaust ventilation	73, 66	58, 48	87, 84
A: MERV13 on continuous supply	67, 63	40, 38	82, 76
B: MERV13 on cont. supply + ESP on FAU	81, 70	73, 50	90, 77
C: MERV16 on blended supply	97, 98	92, 84	97, 99
D: Supply ventilation into return of FAU with MERV16 filter and 20/60 timer	97, 97	93, 96	98, 97
E: MERV13 on return of FAU on 20/60 timer with exhaust ventilation	91, 88	84, 80	93, 93
F: MERV13 on continuous ducted heat pump and exhaust ventilation	96, 95	86, 92	96, 96
G: HRV into return of FAU with HEPA bypass operating on 20/60 timer	79, 78	65, 68	83, 83
Ref + Portable HEPA units	(na), 90	(na), 85	(na), 91

Removal during outdoor air entry to home

- All have lowest performance for 0.3-0.4 um particles as predicted by theory
- Tight shell looks better than the supply MERV13 and HRV

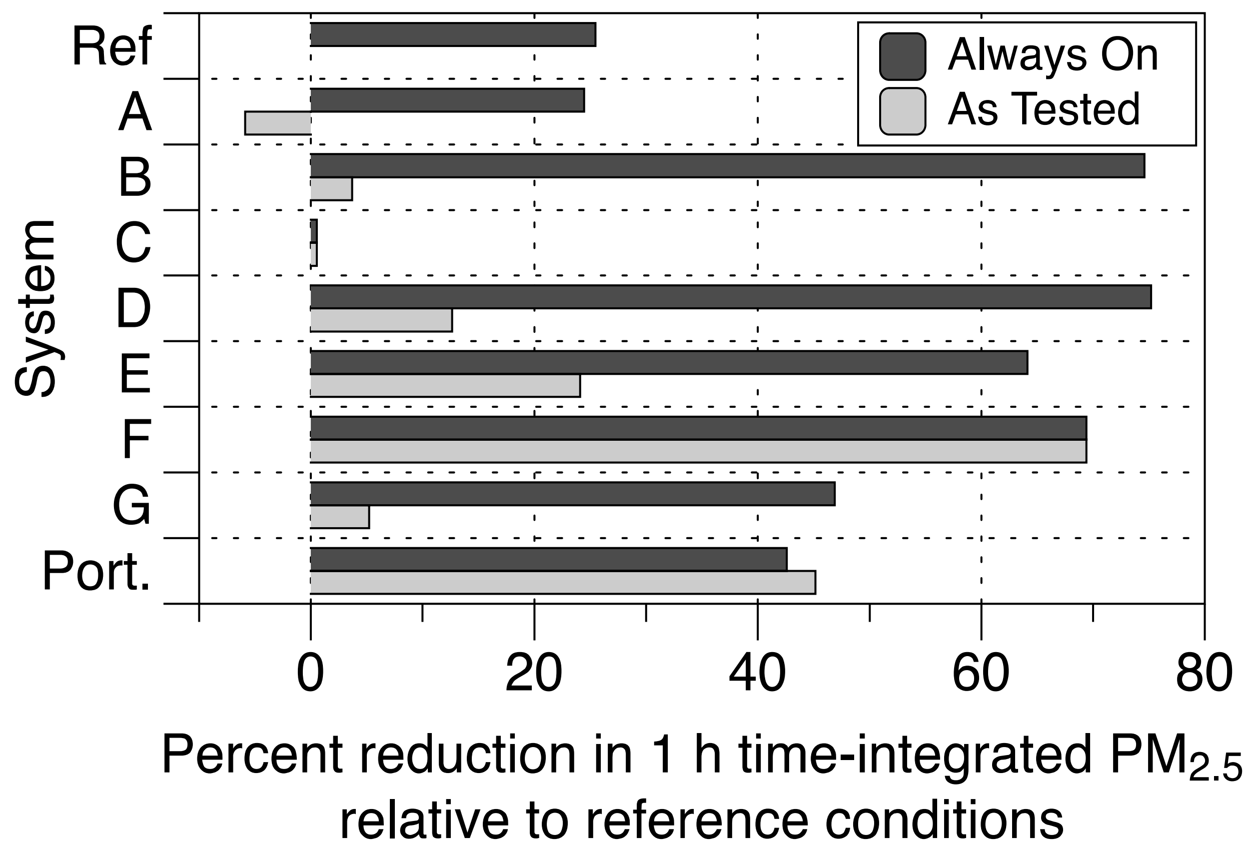


Performance for indoor particles



Summary Results: Cooking Particles

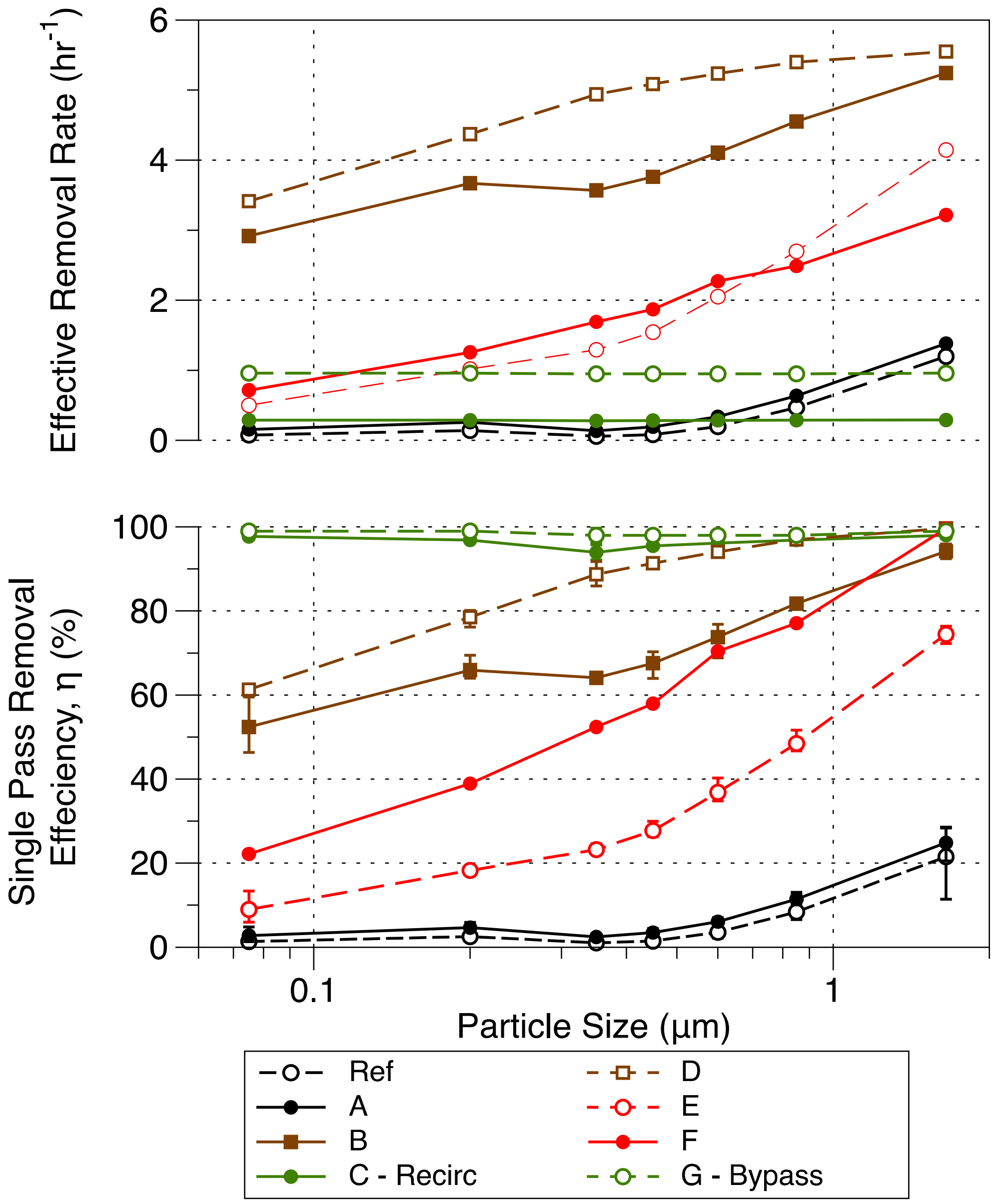
- Sys F and portables: continuous filtration of indoor air
- Sys D & E intermittent filtration of indoor air – depends on timing
- B, D, E effective when operated continuously
- Sys C (MERV16 on blended supply) does almost nothing for indoor particles



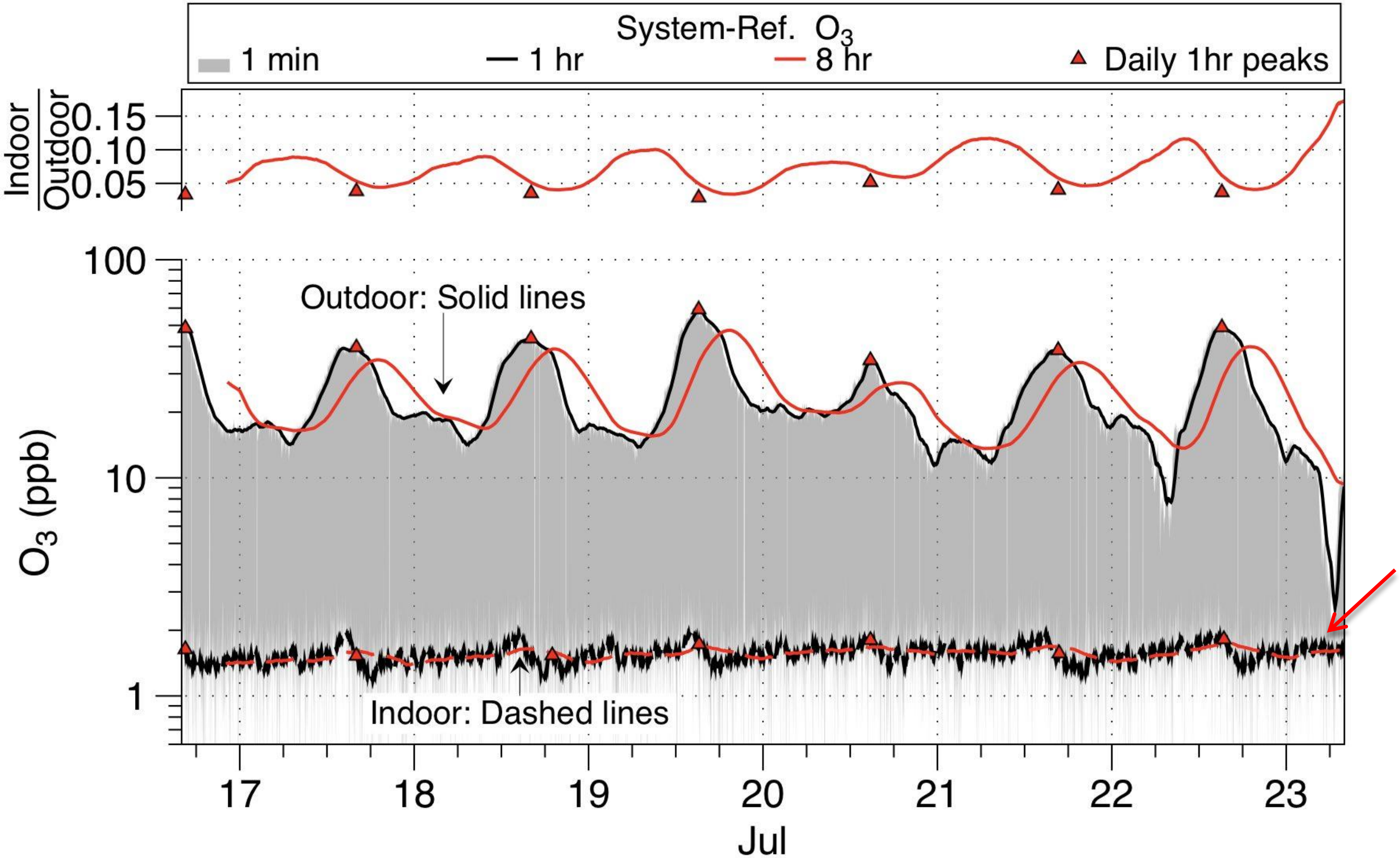
Good performance requires high removal efficiency + airflow

- Filters from C (MERV16) and G (HEPA on bypass) have high removal efficiency, but not enough airflow

- ESP of Sys B and MERV16 of Sys D have both high removal efficiency and enough airflow

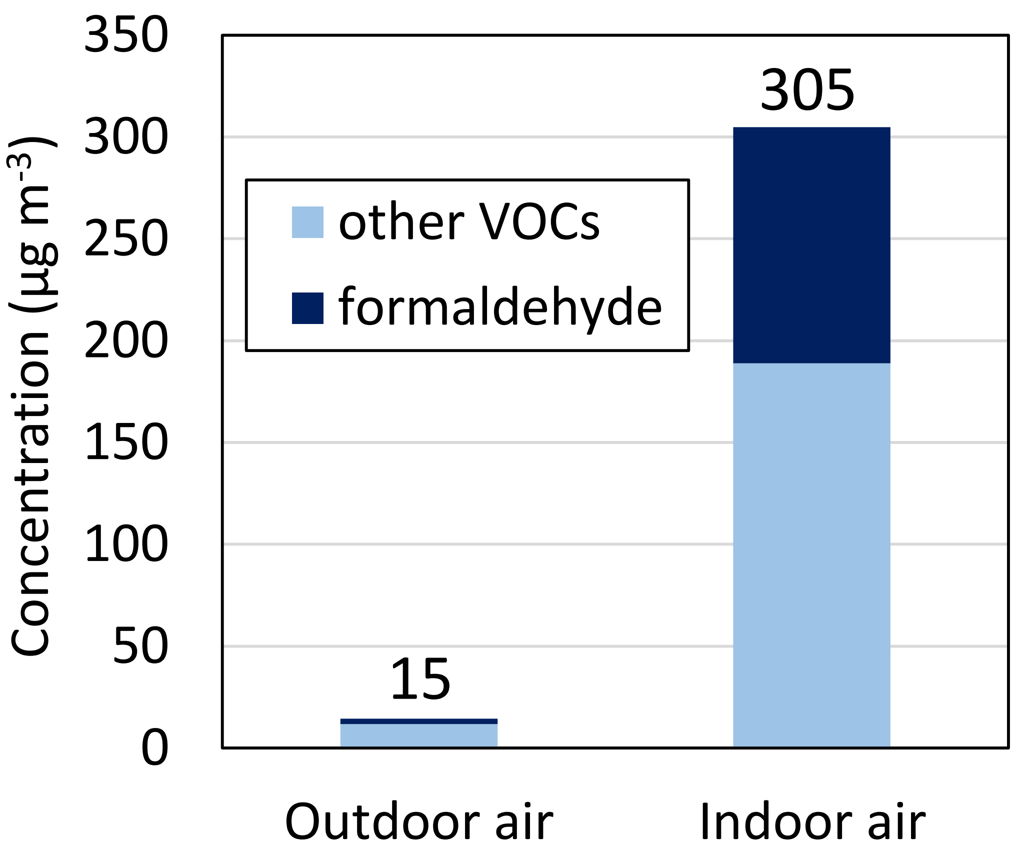


Ozone very low inside. Credit tight envelope.



Ozone was below quant limit indoors for Reference & other systems.

VOC levels were ~20 times higher indoors



- <u>Outdoor VOCs</u>: alkanes and aromatic hydrocarbons (motor vehicle emissions)
- <u>Indoor VOCs</u>: aldehydes, alcohols, terpenoids, siloxanes (material emissions, household products)

VOC removal efficiency

- The relative difference in indoor concentrations between each system and the reference system, $\%\Delta C$, is defined as follows:

$$\%\Delta C = \frac{C(System\ C/D/G) - C(Reference\ \ System)}{C(Reference\ \ System)} \times 100$$

- Main assumption: source strength of VOCs remained constant over the month during which measurements were carried out

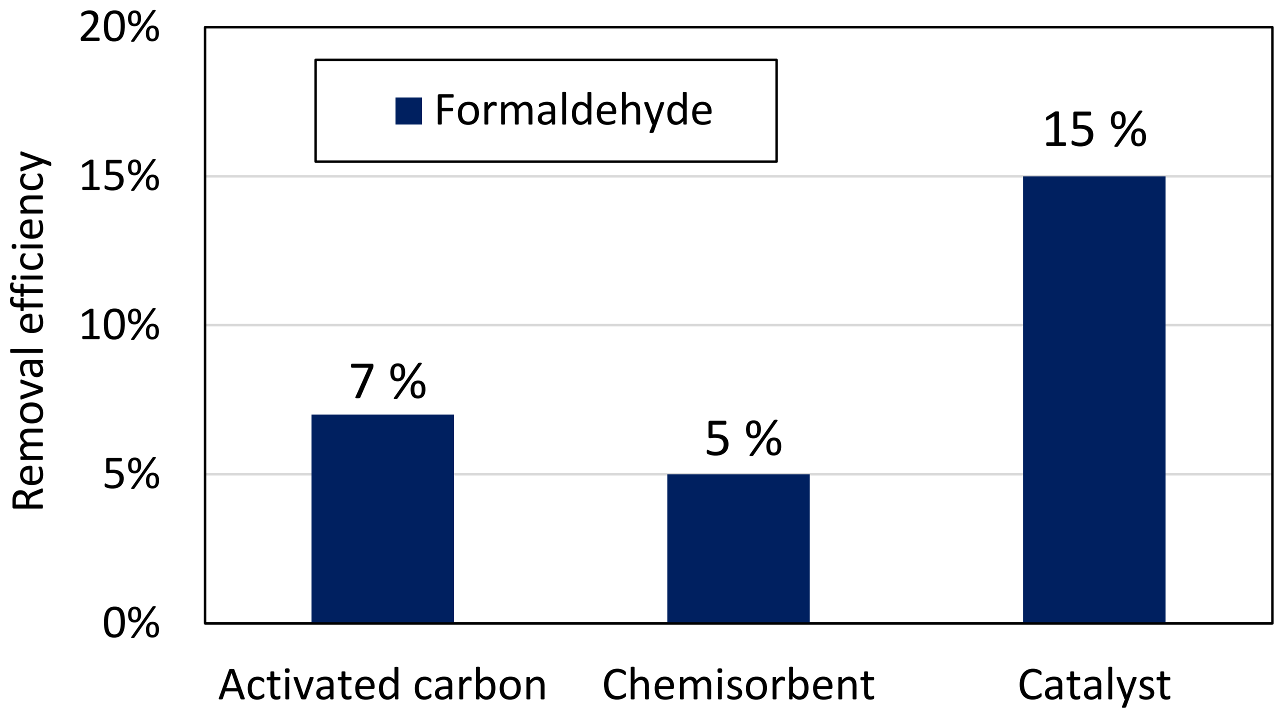
Experimental conditions during VOC tests

			OUTDOOR				INDOOR			
System	ACH (h^{-1})		T (°C)		RH (%)		T (°C)		RH (%)	
	average	st dev	average	st dev	average	st dev	average	st dev	average	st dev
REF	0.29	0.00	24	0	60	1	26	0	44	0

			OUTDOOR				INDOOR			
System	ACH (h^{-1})		T (°C)		RH (%)		T (°C)		RH (%)	
	average	st dev	average	st dev	average	st dev	average	st dev	average	st dev
G	0.31	0.00	27	2	44	8	25	0	45	1
D	0.28	0.01	27	3	48	9	26	1	44	2
C	0.25	0.00	28	1	39	2	26	0	44	0

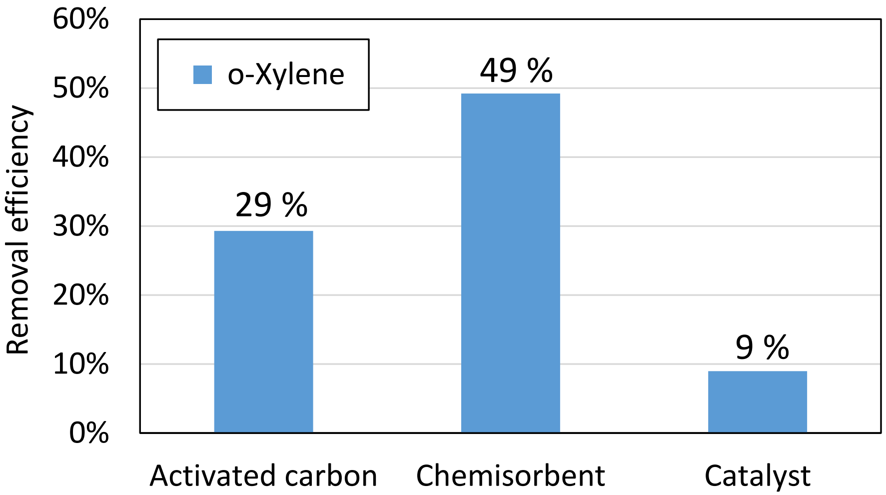
- Temp. and AER variations cannot account for observed VOC reductions. Lower AER for Sys C suggests performance for catalyst better than simple calculation.

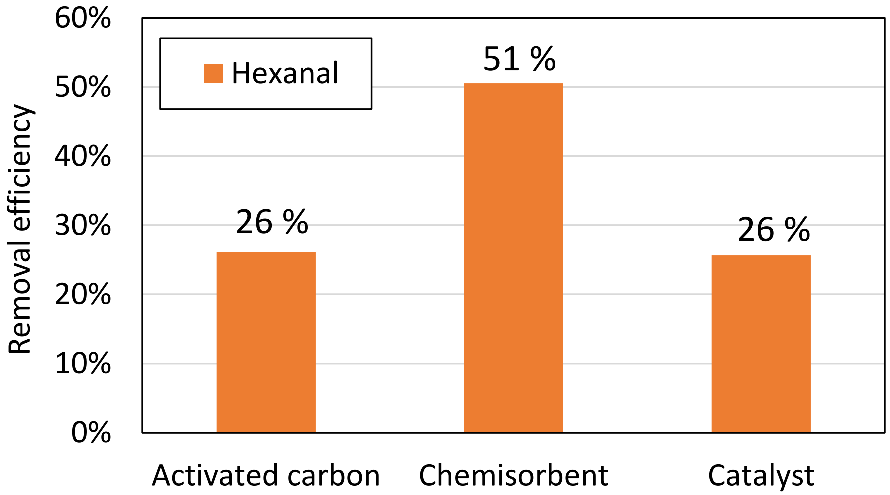
Limited removal efficiency for formaldehyde

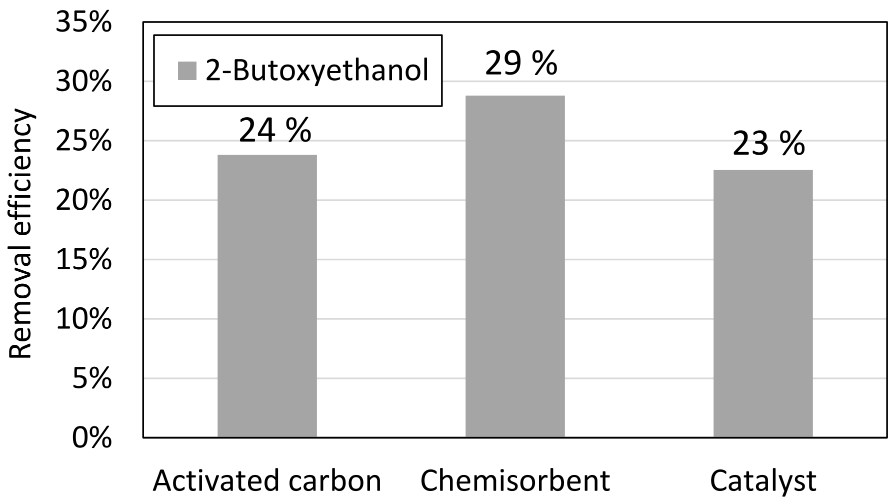


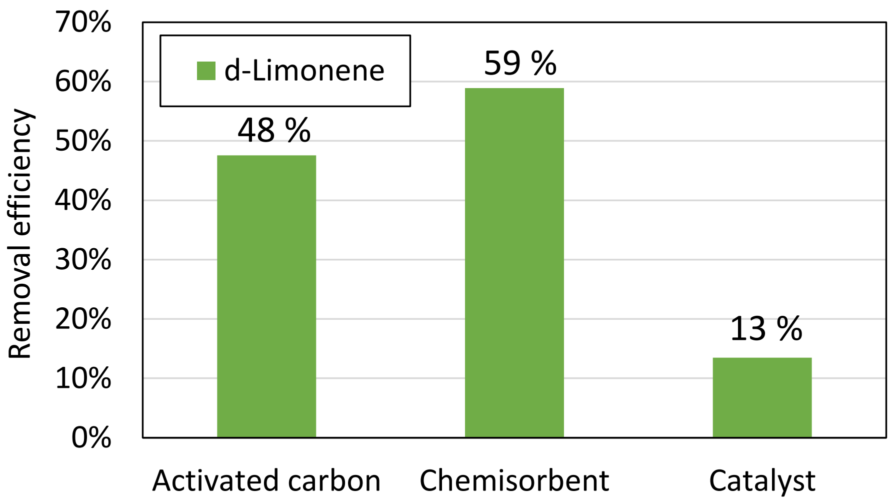
- Formaldehyde is difficult to remove with most air cleaning methods

The three systems showed significant removal efficiencies for many VOCs





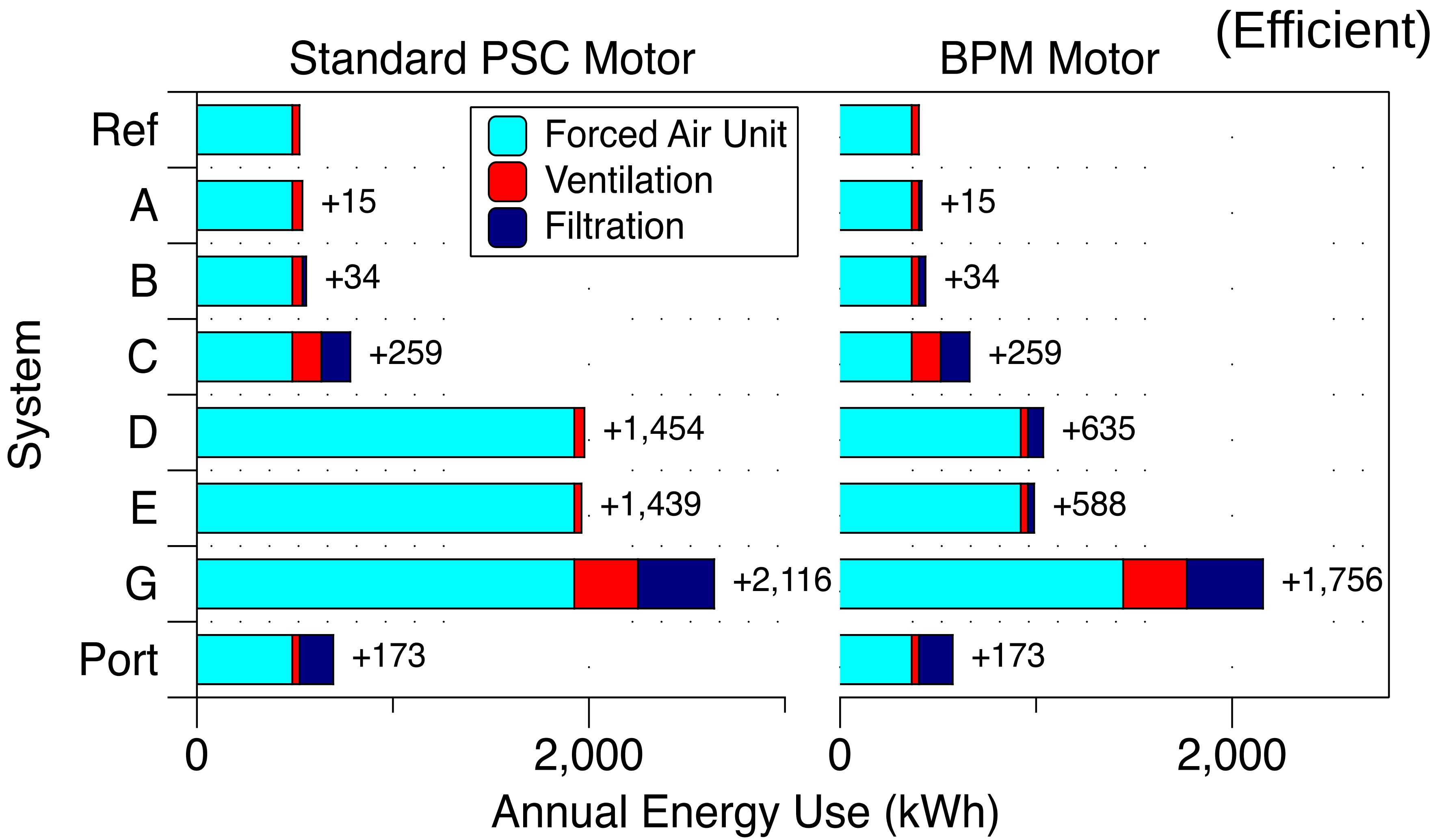




Estimate annual fan energy consumption

- Start with FAU run-time for heating and cooling, determine *extra* hours for intermittent systems.
  - Results from residential energy simulation models
  - Relatively consistent across state b/c systems sized to climate
  - Roughly 800 h baseline; +2400 for 20/60 intermittent
- Multiply by power when operating.

Estimated annual fan energy consumption



Key Results – Outdoor Particles

- The Reference configuration of exhaust ventilation in a moderately tight home reduced concentrations relative to outdoors by 66-73% for $PM_{2.5}$, 48-58% for BC and 84-87% for UFP.
- Supply ventilation with a MERV13 filter yielded slightly higher in-home concentrations of outdoor particles compared to Reference.
- MERV16 on supply ventilation or FAU operating intermittently lowered $PM_{2.5}$ by 97-98%, BC by 84-96% and UFP by 97-99%.
- MERV13 deep pleat filtration on continuous ducted heat pump reduced $PM_{2.5}$ by 95-96%, BC by 86-92% and UFP by 96%.
- A 1" MERV13 filter at the FAU return reduced $PM_{2.5}$ by 88-91%, BC by 80-84% and UFP by 83% compared to outdoors.

BC = Black carbon; UFP = Ultrafine particles

Key Results - Indoor Generated Particles

- Filtration on supply ventilation provides no benefit for indoor generated particles.
- For systems with intermittent filtration, reductions for cooking particles vary with timing of fan operation.
- When operated continuously, all recirculating air systems had some benefits in reducing 1h $PM_{2.5}$
  - MERV4 on FAU reduced 1h $PM_{2.5}$ by ~25%.
  - ESP or MERV16 on FAU reduced 1h $PM_{2.5}$ by ~75%
  - MERV13 on FAU / heat pump reduced 1h $PM_{2.5}$ by 65-70%

Other Key Results – VOCs, Filters & Energy

- Available technologies can cut VOC levels
  - Indoor BTEX levels reduced by three air cleaning systems between 8% and 49% with respect to Reference system
- Need to consider both airflow and single pass removal efficiency for effectiveness
- Possible to get high particle removal rates with low pressure drop filters
- Filtration on ducted supply is lowest energy approach to cleaning outdoor air
- Filtration on forced air system with standard blower motor uses a lot of energy for an efficient home
- Efficient blower motors enable low-energy air cleaning; continuous low speed operation is most efficient